2019 Astrophysics Strategic Technology Gaps

Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
Angular Resolution (UV/Vis/NIR)	The capability to resolve the habitable zones of nearby star systems in the UV/Vis/NIR band, with a large space telescope.	Monolith: 3.5-m sintered SiC with < 3 μm SFE (Herschel); 2.4-m ULE with ~10 nm SFE (HST); Depth: Waterjet cutting is TRL 9 to 14", but TRL 3 to >18". Fused core is TRL 3; slumped fused core is TRL 3 (AMTD). Segmented: (no flight SOA): 6.5 m Be with 25 nm SFE (JWST); Non-NASA: 6 DOF, 1-m class SiC and ULE, < 20 nm SFE, and < 5 nm wavefront stability over 4 hr with thermal control	3	3	Large (4–16 m) monolith and multi-segmented mirrors for space that meet SFE < 10 nm rms (wavelength coverage 400–2500 nm); Wavefront stability better than 10 pm rms per wavefront control time step; CTE uniformity characterized at the ppb level for a large monolith; Segmented apertures leverage 6 DOF or higher control authority meter-class segments for wavefront control.	This gap is likely to be closed by development of large monolithic or segmented telescopes. Aside from angular resolution, large primary mirrors enhance planet sensitivity due to reduction in science integration time with greater collecting areas and throughput enabling probing of a larger number of more distant stars' habitable zones and improved spectral resolution.	LUVOIR, HabEx, or any other large UV/Vis/NIR space observatory.	Demonstration of feasibility and as much risk reduction as possible prior to completion of Astro2020. Per LUVOIR and HabEx Final Reports, TRL 6 in the mid-2020's would be needed.
Coronagraph Contrast	The capability to suppress starlight with a coronagraph to the level needed to detect and spectrally characterize Earth-like exoplanets in the habitable zones of Sun-like stars.	unobscured pupil: 6×10^{-10} raw contrast at 10% bandwidth, angles of 3-15 λ/D (HLC demo in HCIT); obscured pupil: 1.6×10^{-9} raw contrast at 10% bandwidth across angles of 3-9 λ/D (WFIRST)	4	3	Maximized science yield for a direct imaging telescope/mission. $\leq 10^{-10}$ raw contrast, >10% throughput, IWA $\leq$ 3 λ/D, obscured/segmented pupil	This gap is likely to be closed by improvements in coronagraph masks and optics, wavefront control, data post-processing.	LUVOIR, HabEx, or any other coronagraph-based exoplanet direct-imaging mission.	Demonstration of feasibility and as much risk reduction as possible prior to completion of Astro2020. Per LUVOIR and HabEx Final Reports, TRL 6 in the mid-2020's would be needed.
Coronagraph Contrast Stability	The capability to maintain the deep starlight suppression provided by a coronagraph for a time period long enough to detect light from an exo-Earth.	WFIRST CGI demonstrated ~10-8 contrast in a simulated dynamic environment using LOWFS (which obtained 12 pm focus sensitivity) SIM and non-NASA work has demonstrated nm accuracy and stability with laser metrology Capacitive gap sensors demonstrated at 10 pm 80 dB vibration isolation demonstrated Gaia gold gas microthrusters and LISA pathfinder colloidal microthrusters can reduce vibrations	3	3	Contrast stability on time scales needed for spectral measurements (possibly as long as days). Achieving this stability requires an integrated approach to the coronagraph and telescope, possibly including wavefront sense/control, metrology and correction of mirror segment phasing, vibration isolation/reduction This stability is likely to require wavefront error stability at the level of 10-100 pm per control step (of order 10 minutes).	This gap is likely to be closed by a combination of many factors in a coronagraph/observatory system, including active wavefront control at the coronagraph level, thermal control, active and passive ultra-stable structures, and disturbance isolation/ reduction.	LUVOIR, HabEx, or any other coronagraph-based exoplanet direct-imaging mission.	Demonstration of feasibility and as much risk reduction as possible prior to completion of Astro2020. Per LUVOIR and HabEx Final Reports, TRL 6 in the mid-2020's would be needed.

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Cryogenic Readouts for Large-format Far-IR Detectors	Readout schemes including cryogenic multiplexing for arrays of large-format Far-IR detectors need to be developed.	Readout schemes using HEMT or SiGe amplifiers and frequency-multiplexed resonant circuits are in development. A few hundred channels per 1 mW HEMT amplifier have been demonstrated. Low power dissipation at 4 K is required. For TES-based detectors a microwave SQUID multiplexer using frequency division, time division or code division multiplexing is needed. Frequency division multiplexing is well advanced and can meet the needs of Origins when scaled to 2000 pixels (resonators) per 4 GHz channel.	4	3	Near-term, this scheme should result in 2000 pixels per amplifier channel **(enabling)**, 3000 pixels/channel **(enhancing)**.HEMT amplifiers from Low Noise Factory can achieve 10 dB with 0.38 mW of dissipation at 4 K.	Sensitivity reduces observing times from many hours to a few minutes (≈ 100× faster), while array format increases areal coverage by ×10-100. Overall mapping speed can increase by factors of thousands. Sensitivity enables measurement of low-surface-brightness debris disks and protogalaxies with an interferometer. This is enabling technology. Suborbital and ground-based platforms can be used to validate technologies and advance TRL of new detectors.	FIR detector technology is an enabling aspect of all future FIR mission concepts, and is essential for future progress. This technology can improve science capability at a fixed cost much more rapidly than larger telescope sizes. This development serves Astrophysics almost exclusively (with some impact on planetary and Earth studies). Many synergies exist with similar developments for x-ray microcalorimeters	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission PDR anticipated in the mid-2020s.
Fast, Low-Noise, Megapixel X-ray Imaging Arrays with Moderate Spectral Resolution	Lynx requires X-ray imaging arrays covering wide fields of view (> 60 x 60 mm) with excellent spatial resolution (i.e. <16 micron pixels, or equivalent X-ray position resolution), and moderate spectral resolution (comparable to modern scientific CCDs). These detectors must have good detection efficiency across the soft X-ray band pass, from 0.2-10 keV, and excellent detection in the low-energy (0.2 – 1 keV) end of this band pass is essential. Therefore, optical blocking filters with minimal attenuation of soft X-ray will also be required. Fast frame rates (i.e. > 30 -100 frame/s) to minimize pile-up for demanding effective areas that are ~30x that of Chandra are also required.	Silicon active pixel sensors (APS) currently satisfy some of the requirements, but further work is needed to meet all requirements simultaneously. APS with 36-μm pixels are at TRL 6, but noise levels are still too high, and sensitivity to soft X rays needs to improve. Sparsified readout, limited to pixels with signals, allows fast frame rates and is at TRL 3.	3	3	• Lynx requires large format X-ray detectors with sufficient spatial resolution so as not to compromise the imaging performance of the Lynx optics (notionally with 0.5” half power diameter, HPD); • Multi-chip abuttablility to build detector surface approximating best focal surface for the mirrors; • roughly Fano-limited spectral resolution in the 0.2-10 keV energy band; actual energy resolution requirement is still TBD, but it will be roughly CCD-like or perhaps slightly less stringent • Frame rates > 30~100 frames/s; • Optical-blocking filters with minimal X-ray absorption above 0.2 keV; Radiation hardness supporting 5-20 years of science operations at Chandra-like or L2 orbit	Enables X-ray imaging of wide fields with high spatial resolution and sufficient spectral resolution to meet science goals of strategic X-ray missions.	Lynx, Joint Astrophysics Nascent Universe Satellite (JANUS) / X-ray Time Domain Explorer (XTiDE) -like, or any other focused X-ray optics, or coded-aperture wide-field X-ray-monitoring, or X-ray-grating mission.	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission Preliminary Design Review (PDR) anticipated in the mid-2020s.

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High-efficiency X-ray Grating Arrays for High-resolution Spectroscopy	Light-weight, high-efficiency (> 40-50%), large-format X-ray grating arrays enable high spectral resolving power R > 5000 in the soft X-ray band (~ 0.2 - 2 keV) for absorption- and emission-line spectroscopy using large X-ray telescopes. These would provide the resolving power needed to address key science goals in the soft X-ray band, such as studying the physical state of baryons in galactic halos and in the Cosmic Web, detailing matter and energy feedback from supermassive black holes (SMBH), and characterizing stellar lifecycles from birth to death.	Proven technologies (grating spectrometers on Chandra and X-ray Multi-mirror Mission-Newton, XMM-Newton) fall short in efficiency, collecting area, and resolving power, by factors of 5-10. High-efficiency gratings have been demonstrated that place > 40% of the incident soft X-ray light into the diffracted orders. Separately, high-spectral-resolving-power gratings have achieved resolving powers > 10,000 in the soft X-ray band Current technology readiness is assessed to be at TRL 4.	4	4	Lightweight, high efficiency (~40% or more), large-format grating arrays with high spectral resolving power (R>5000) in the soft X-ray band (0.2 - 2 keV) for absorption- and emission-line spectroscopy using large X-ray telescopes.	Spectrometers achieving R > 5000 throughout the soft X-ray band are mission-enabling, as microcalorimeters cannot achieve that. Priority science goals for soft X-ray spectroscopy are studying the physical state of baryons in galactic halos and in the Cosmic Web, detailing matter and energy feedback from SMBH, and characterizing stellar lifecycles from birth to death.	A spectrometer using gratings with this performance is envisioned for Lynx, has been studied by NASA as a Probe, has been proposed for an Explorer, and will be flown on the Off-plane Grating Rocket Experiment (OGRE).	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission Preliminary Design Review (PDR) anticipated in the mid-2020s.
High-Resolution, Large-Area, Lightweight X-ray Optics	The science of Lynx requires a large-throughput mirror assembly with sub-arcsec angular resolution. These future X-ray mirrors have a set of requirements, which collectively represent very substantial advances over any currently in operation or planned for missions other than Lynx. Of particular importance is achieving low mass per unit collecting area, while maintaining Chandra-like angular resolution.	High Resolution Chandra optics: • Angular resolution <~ 0.5 arcsec; • Effective area 750 cm^2 at 1 keV; and • Mirror mass 951 kg. There are multiple efforts underway to develop lightweight, high angular resolution X-ray optics. These efforts include single substrate development to full assemblies, and includes silicon and glass segmented, adjustable segmented and full-shell solutions, among others. TRL 2-3 **(and approaching TRL 4**) for various technologies for high-resolution, lightweight mirrors mentioned above. To date, no effort has yet demonstrated sub-arcsec resolution for an optical assembly with reasonable effective area of lightweight X-ray optics.	3	3	• Mirror technologies must be scalable to at least 2m^2 effective area-class assemblies; and • Overall mirror angular resolution of order 0.5 arcsec or better on-axis. A demonstration is desired in the form of an adequate engineering unit involving a subset of the outermost and innermost elements **for a large (3-m diameter) assembly**. The goal would be to provide realistic and adequate X-ray measurements that do not rely on optimistic extrapolations.	These X-ray optics will enable study of the early universe to complement the James Webb Space Telescope (JWST) and other observatories, maintain US leadership in lightweight X-ray optics for space, and facilitate future missions. Most of the Lynx observations do not require significantly better resolution than the proven Chandra capabilities. Rather, it is the significant increase in collecting area at a reasonable mass, combined with unprecedented spectral performance, while maintaining high angular-resolution that makes Lynx a true successor to Chandra and synergistic to a multitude of other observatories (both in-space and ground-based).	This is an enabling technology for Lynx. This technology is also applicable to Probe-class, Explorer-class, **and Suborbital** missions. Once developed, there are numerous potential scientific applications). Once developed (and no longer virtual optics) cost estimates will become much more realistic and lower. Moreover, the development is urgent for the future of X-ray Astronomy in the USA. Without adequate development, proposed missions will be costed based on virtual optics, and thus priced much higher than they would be given an adequate development program.	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission PDR anticipated in the mid-2020s.

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Large-Format, High-Resolution UV/Vis Focal Plane Arrays	The High Definition Imager UVIS-channel and LUVOIR UV Multi-object Spectrograph near-UV channel focal plane arrays require a large number (>20) of large format (8k x 8k) detectors with small pixels (<7 µm). High-speed readout over programmable regions-of-interest are desired to enable fine guiding and high-speed science objectives.	While commercial off-the-shelf CMOS arrays of this format exist, they have not be adopted for spaceflight, nor do they exhibit optimal noise performance for scientific operations. Development challenges include optimizing detector and readout electronics for low noise performance, and flight qualifying large-format detector packages.	4	4	• Array Format: 8k x 8k, three-side buttable • Pixel Size: < 7 µm • Read Noise: ~1 e- • Dark Current:~$1x10^{-4}$ e-/pixel/s • Operating Temperature: > 150 K Design and fabricate an 8k x 8k x 6 µm CMOS detector and associated readout electronics in a three-side-buttable package. Verify detector sensitivity and noise performance. Complete functional, performance, and radiation testing to achieve TRL 5. Fabricate additional sensors and electronics and integrate into a single focal-plane array. Complete functional, performance, and environmental qualification testing to achieve TRL 6. (see LUVOIR final report for more detailed plan, schedule, and cost)	Many missions would benefit from large format, high-resolution, low noise focal plane arrays.	LUVOIR, HabEx, others	Per LUVOIR Final Report, TRL 6 prior to Phase A start in 2025 is required. See LUVOIR Final Report for detailed development plan recommendations, schedule, and cost estimate.

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Large-Format, High-Spectral-Resolution, Small-Pixel X-Ray Focal Plane Arrays	X-ray microcalorimeters are needed to allow spatially resolved spectroscopy with Lynx. The arrays need to cover a wide field (> 5 arcmin) and with spatial resolution matching future X-ray optics (<~ 1 arcsec). The X-ray focal-plane-array pixels need to provide excellent spectral resolution (<~ 3 eV Full-Width at Half-Maximum, FWHM, in the 0.2 – 10 keV band). Different regions of the array should be optimized for different types of measurements in a hybrid configuration. The innermost region should have the smallest pixels with an energy range extended to > 7 keV. The outer region should be optimized for soft X-rays up to 2 keV, ideally extending the field-of-view to ~ 20 arc-minutes. A separate sub-array should be optimized for the best energy resolution up to 0.8 keV, providing better than 0.3 eV [FWHM] energy resolution.	Fabrication of arrays has been demonstrated with 37.5 kilo-pixels on a 50-micron pitch ("Main Array" pixels) and 10 kilo-pixels on a 25-micron pitch ("Enhanced Main Array" pixels), these pixels being optimized for energies up to 7 keV. Sub-arrays of 1.6 kilo-pixels on a 50-micron pitch ("Ultra-Hi-Res Array" pixels) have been produced optimized for energies below 1 keV. Prototype Main array pixels with twenty absorbers attached to a single TES have demonstrated 3.4 eV FHWM energy resolution. Ultra-Hi-Res pixels have demonstrated 0.3 eV energy resolution at low energies. In the context of the required array size, the array fabrication is currently TRL 4. However the energy resolution performance still needs to be demonstrated with the required read-out circuitry (Nyquist inductors) suitable for multiplexed read-out, the discrimination of hydra pixels down to < 300 eV, and 0.3 eV energy resolution above 0.5 keV all need to be demonstrated before TRL-4 can be claimed for all the microcalorimeter sub-arrays. Small arrays (36 pixels) of much larger microcalorimeter pixels, is at TRL 9 (Hitomi). Multiplexing with microwave Superconducting QUantum Interference Devices (SQUIDs) in resonator circuits at GHz frequencies will accommodate the read out of hundreds or maybe a thousand sensors per readout channel, and thus provides a path to reading out much larger arrays. This has been demonstrated reading out 130 pixels (TRL-4 but 3 with respect to Lynx requirements). TESs and magnetic calorimeters are two of the leading thermal-sensor technologies with potential to meet the Lynx requirements, and both can be read out using microwave SQUIDs in GHz resonators. References available at: https://www.spiedigitallibrary.org/journals/journal-of-astronomical-telescopes-instruments-and-systems/current?SSO=1#SpecialSectionontheLynxX-RayObservatory	3	3	The primary objective for Lynx is large-format arrays with pixel count > 100k and spectral resolution < 3 eV FWHM at 0.2 – 10 keV. This likely requires a high degree of multiplexing, both thermal and electrical: <u>Thermal multiplexing:</u> Sensors attached through varying thermal conductances (hydras) to multiple absorbers, allowing pixel identification across the entire energy band, up to a multiplexing factor of 25:1, with energy resolution < 3 eV for pixel pitch < 50 µm and < 2 eV for pixel pitch < 25 µm. <u>Electrical multiplexing:</u> • Readout using microwave resonators, such as with microwave SQUIDs. Desired multiplexing factor is > 1000:1 for TESs with low slew rates, and > 400:1 for high slew-rate hydras.	Science benefits identified for International X-ray Observatory (IXO) in "New Worlds, New Horizons in Astronomy and Astrophysics" (NWNH) and Lynx in the 2014 Astrophysics Roadmap update. The more advanced the multiplexed readout becomes, the more engineering benefits there are. These benefits include having less-demanding cryogenic requirements; and also lower instrument mass, power, and cost for the cryogenics and readout.	Lynx. The technology is also synergistic with an enabling technology for the US contribution to Athena.	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission Preliminary Design Review (PDR) anticipated in the mid-2020s.

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Large-Format, Low-Noise and Ultralow-Noise Far-IR Direct Detectors	The most important technology for the FIR/submillimeter is large-format detectors that operate with high efficiency (≥ 80%), low noise, and relatively fast time constant. Arrays containing thousands of pixels are needed to take full advantage of spectral information content. Arrays containing tens of thousands of pixels are needed to take full advantage of the focal plane available on a large, cryogenic telescope. Detector sensitivity is required to achieve background-limited performance, using direct (incoherent) detectors to avoid quantum-limited sensitivity.	Kilopixel arrays at lower sensitivity are at TRL ~5, but demonstrated array architectures are lagging at TRL ~3. (Staguhn, 2018) Sensitive (noise-equivalent power ,NEP, of low 10^{-19} W/√Hz), fast detectors (TES bolometers, and MKIDs in kilo pixel arrays) are at TRL 3.(Suzuki, 2015), (Baselmans, 2017)	3	3	Detector format of at least 10^4 pixels with high fill-factor and sensitivity (NEP) of ~1×10^{-19} W/√Hz are needed for wide-band photometry. **(enabling)** Detector sensitivities with NEP of ≈ 3×10^{-20} W/√Hz are needed for spectroscopy (**enabling**), available in a close-packed configuration in at least one direction. NEPs of 3×10^{-21} W/√Hz would enable background-limited sensitivity(Echternacht, 2018) **(enhancing)** The detector system should be scalable to enable ~million-pixel total format (10k~50k pixels per sensor) in a large mission. Array size of 1×10^4 is **enabling** and 5×10^4 is **enhancing** Fast detector time constant (~200 μs) is needed for Fourier-transform spectroscopy.	Sensitivity reduces observing times from many hours to a few minutes (≈ 100× faster), while array format increases areal coverage by ×10-100. Overall mapping speed can increase by factors of thousands. Sensitivity enables measurement of low-surface-brightness debris disks and protogalaxies with an interferometer. This is enabling technology. Suborbital and ground-based platforms can be used to validate technologies and advance TRL of new detectors.	FIR detector technology is an enabling aspect of all future FIR mission concepts, and is essential for future progress. This technology can improve science capability at a fixed cost much more rapidly than larger telescope sizes. This development serves Astrophysics almost exclusively (with some impact on planetary and Earth studies).	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission PDR anticipated in the mid-2020s.
Large-Format, Low-Noise, High-QE Far-UV Detectors	Large-format, low-noise detectors in the Far-UV (~100-200 nm) are required to enable LUVOIR Far-UV imaging and spectroscopy science goals. Micro-channel plate detectors have been baselined as the lowest-risk detectors.	Large-format, low noise microchannel plates are being developed as part of numerous sounding rocket experiments. Remaining development challenges include the demonstration of GaN microchannel plates to enable the redder end of the far-UV detector, and demonstrating a tiled micro-channel plate focal plane array. New funnel-style micro-channels have also been shown to improve quantum efficiency by 50% (Matoba et al. 2014) and their incorporation into the baseline MCP architecture should be explored. **SISTINE, FORTIS, CHESS:** Suborbital sounding rocket missions that have incrementally matured aspects of MCP detector technology, including array size, photocathode sensitivity, and read-out electronics count rates (TRL 9)	4-9	4,6	Tile Size: 200 x 200 mm Quantum Efficiency: >30% between 100-200 nm. Design and fabricate a 200 mm x 200 mm CsI microchannel plate detector, 200 mm x 200 mm GaN microchannel plate detector, and all associated readout electronics. Verify performance of each detector. Integrate both microchannel plate detectors into a single focal plane array, with a maximum gap size of 15 mm. Complete functional, performance, and environmental qualification testing to bring the Large-format Microchannel Plate Detector technology component to TRL 6. (see LUVOIR final report for more detailed plan, schedule, and cost)	MCPs have long been the "gold standard" for UV science observations. Continued improvement of these detectors would have science and programmatic benefits for any mission operating in the UV.	LUVOIR, HabEx, any mission with UV science.	Per LUVOIR Final Report, TRL 6 prior to Phase A start in 2025 is required. See LUVOIR Final Report for detailed development plan recommendations, schedule, and cost estimate.

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Next-Generation Large Format Object Selection Technology for Multi-Object Spectrometers for LUVOIR	The multi-object spectroscopy capability on LUVOIR is enabled by an array of microshutters, similar to those used on JWST/NIRSpec.	An existing technology development effort is already funded to mature the development of "next generation" microshutter arrays to TRL 4, and incorporates multiple design improvements over the JWST-style microshutters. These next-generation microshutters will also fly on the FORTIS sounding rocket in 2022. Once the existing technology development effort is completed, the remaining challenges include fabricating large-format (840 x 420) arrays and completing environmental qualification.	3	3	Array Format: 840 x 420, two-side buttable Upon completion of the existing development effort, design and fabricate a large format (840 x 420) microshutter array with accompanying control electronics. Complete functional, performance, and environmental qualification testing to bring the Next-generation Microshutter Array technology component to TRL 6. (see LUVOIR final report for more detailed plan, schedule, and cost))	Enables large-format multi-object spectroscopy for any mission platform.	LUVOIR	Per LUVOIR Final Report, TRL 6 prior to Phase A start in 2025 is required. See LUVOIR Final Report for detailed development plan recommendations, schedule, and cost estimate.
Vis/NIR Detection Sensitivity	The capability to detect single photons in the Vis and NIR to enable imaging and spectroscopy of Earth-like exoplanets.	Vis: 1k×1k silicon EMCCD detectors provide dark current of 7×10-4 e-/px/sec; CIC of 0.01 e-/px/frame; zero effective read noise (in photon counting mode) after irradiation when cooled to 165.15 K (WFIRST); 4k×4k EMCCD fabricated but still under development NIR: HgCdTe photodiode arrays have read noise ≲ 2 e- rms with multiple nondestructive reads; 2k×2k format; dark current < 0.001 e-/s/pix; very radiation tolerant (JWST);HgCdTe APDs have dark current ~10–20 e-/s/pix, RN << 1 e- rms, and < 1k×1k format Cryogenic superconducting photon-counting detectors (MKID,TES): 0 read noise/dark current; radiation tolerance is unknown; <1k×1k format			Near IR (900 nm to 2.5 μm) and visible-band (400-900nm) extremely low noise detectors for exo-Earth spectral characterization with Integral Field Spectrographs. NIR Read noise << 1 e- rms, dark current noise < 0.001 e-/pix/s, Vis band read noise < 0.1 e- rms; CIC < 3×10-3 e-/px/frame; dark current < 10-4 e-/px/sec , functioning in a space radiation environment over mission lifetime; large ≥ 2k×2k format	Single-photon counting detectors in the Vis/NIR bands allow characterization of very faint objects.	LUVOIR, HabEx, other exo-Earth direct imaging missions.	Demonstration of feasibility and as much risk reduction as possible prior to completion of Astro2020. Per LUVOIR and HabEx Final Reports, TRL 6 in the mid-2020's would be needed.

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Advanced Millimeter-Wave Focal-Plane Arrays for CMB Polarimetry	The Inflation Probe (IP) requires arrays of detectors with background-limited sensitivity, dual-polarization detection capability, and control of systematic errors at multiple frequencies between ~30 and ~600 GHz for foreground removal. Architectures must be scalable to large arrays for the requisite sensitivity. Simultaneous multiband operation, high multiplexing factors, and efficient detector and readout focal-plane packaging represent desirable design qualities. Detector systems must be compatible with the space environment. This includes low dielectric exposure to low-energy electrons and robust performance in the presence of cosmic rays. Continued deployment in ground-based and balloon-borne platforms will benefit development efforts.	A great deal of progress has been made with a variety of approaches, including feedhorn and antenna-coupling waveguide probes, and filled absorber structures. TESs are currently the leading candidate technology for the detecting element in these integrated sensors. Arrays of several thousand detectors are operating in ground-based Cosmic-Microwave-Background (CMB) - polarization experiments. Balloon experiments E and B Experiment (EBEX) and Suborbital Polarimeter for Inflation Dust and the Epoch of Reionization (Spider) have demonstrated two TES architectures in the environment closest to space. Primordial Inflation Polarization Explorer (PIPER) will soon demonstrate a third. Fabrication of TES arrays on 150-mm diameter substrates, which addresses pixel-count scalability, is now maturing at multiple fabrication foundries. However, no fielded 150-mm arrays exist at this time.	4	3	The detectors must demonstrate high efficiency, background-limited sensitivity, and linearity over a wide spectral range (~30 to ~600 GHz), while at the same time controlling systematic errors to a level sub-dominant to the instrument statistical-noise floor. The technology must demonstrate extremely low levels of polarized-beam systematic errors to achieve this goal. The technology must be compatible with space-borne operation, and provide appropriate magnetic shielding, cosmic-ray immunity, vibration tolerance, and excellent noise stability. Process uniformity, high detector efficiency, and high yield are also important. One technical development that would have a large impact on instrument design is a reduction of the TES detector-to-readout interconnects at the milliKelvin stage. Current TES readout schemes demand a large number of additional hardware elements, which require interconnects and an associated mechanical support structure. Technical approaches that do away with additional readout hardware elements will reduce the mass, volume, and complexity of the entire instrument. Integrated fabrication of TES detectors and SQUID readouts represents one avenue to achieve this goal.	Measurement of CMB polarization to search for evidence of, and characterize, Inflation is a top NASA priority. Such detectors are a key enabling technology. A space-borne measurement can probe for a polarization pattern imprinted by a background of GWs generated at the time of Inflation in the early universe. Polarization measurements on finer angular scales probe large-scale structure sensitive to neutrino mass and dark energy.	These are needed for measuring CMB polarization to search for and characterize the faint polarized signature of Inflation. The targeted mission is IP as recommended in the NWNH report. Other possibilities include Explorer and international CMB-polarization and absolute-spectrum experiments. Development also has technological overlaps with superconducting far-IR and X-ray detectors.	**Named missions:** IP (2020s) **Development needed for 2020 Decadal:** Yes, IP **Other drivers:** IP technology development is a NWNH priority that was recently revisited by the mid-Decadal review. US contribution to the Japanese Aerospace eXploration Agency (JAXA) mission Lite (light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD) is already in a phase A study through the Explorer's program. An additional Explorer proposal to contribute to a European Space Agency (ESA) mission is likely this year.
Detection Stability in Mid-IR	The capability to detect mid-infrared light with ultrastable detectors to carry out transit spectroscopy of terrestrial exoplanets in the Habitable Zone of M-dwarf stars.	JWST/MIRI is expected to achieve 10-100 nm transit stability. Spitzer IRAC Si:As detector data have demonstrated about 60 ppm precision in transit observations of several hours			Ultrastable detectors (< 10 ppm over 5 hours) for the mid-infrared band (7 - 20 microns) enabling transit spectroscopy of rocky exoplanets in the Habitable Zone of M-dwarfs.		Origins Space Telescope or other transit spectroscopy mission	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission PDR anticipated in the mid-2020s.

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Heterodyne FIR Detector Arrays and Related Technologies	Heterodyne FPAs are needed for high-sensitivity, spectrally resolved mapping of interstellar clouds, star-forming regions, and solar system objects including comets. These arrays require mixers with low noise-temperature and wide intermediate frequency (IF) bandwidth, local oscillators (LOs) that are tunable but which can be phase-locked, and accompanying system technology including optics and low-cost, low-power digital spectrometers. Specifically, LO sources at frequencies above 2 THz that can generate ≥ 10 μW of power will be essential for large-format heterodyne receiver arrays to observe many spectral lines important for COR (e.g., HD at 2.7 THz and OI at 4.7 THz).	For SOFIA, 10-pixel receivers have been developed for flight; arrays of 64 pixels are approaching TRL ~4. LOs above 2 THz are at TRL 2. Far IR SIG: Heterodyne arrays are used routinely for infrared observations in platforms including SOFIA and Herschel. The largest arrays that have been used in these settings (such as upGREAT on SOFIA) contain fewer than 20 pixels. Existing systems have good performance but power requirements far exceed what is available in spacecraft, especially if there are more pixels in arrays than currently employed. Currently LOs located at 4 K dissipate 4 mW per pixel. Near term this is expected to decrease to 1 mW per pixel. Longer term this is expected to decrease to 0.5 mW per pixel. The heterodyne instrument is no longer in the Origins baseline, but is a possible Upscope for Origins.	4	4	Tunable-bandwidth array receivers for operation at frequencies of 1-5 THz. Arrays of 10 to 100 pixels are required to build on the discoveries of Herschel and exploit the sub-millimeter/FIR region for astronomy. Should include optics and accompanying system components. For mixers, IF bandwidths of 8 GHz at shorter wavelengths (< 100 microns) are essential to analyze entire galactic spectrum in one observation. Sensitive mixers not requiring cooling to 4 K (e.g., based on high critical temperature superconductors) will be essential for application on space platforms, especially with the benefit of increased IF bandwidth. For LOs, sources with output power levels ≥ 10 μW at frequencies above 2 THz. For digital spectrometers, 8 GHz bandwidth with > 8000 spectral channels, and < 1W power per pixel will be necessary for large arrays used in space missions. Cryogenic IF amplifiers with reduced power dissipation also needed, e.g. 0.5 mW for 8 GHz bandwidth. Far-IR SIG: SIS- and HEB-based mixer arrays with up to hundreds of pixels, coupled with low power, broadly tunable local oscillators. Increased IF bandwidth of mixers, with minimum of 8 GHz bandwidth required at frequencies about 3 THz. Low-power digital spectrometer systems with frequency coverage of 4 GHz in general, and up to 8 GHz for higher-frequency systems.	Ability to observe and map spectral lines (such as OI at 4.774 THz) to study star formation and galactic chemical evolution. Observations of transitions of water are necessary to probe the early phases of planet formation, and to determine the origin of the Earth's oceans. Development of such systems and associated technology will make imaging observations over 10× faster. They will also significantly benefit laboratory spectroscopy and biomedical imaging. Far-IR SIG: Increasing the pixel count by 1-2 orders of magnitude over existing instruments will dramatically increase imaging efficiency for high spectral resolution observations. Increased instantaneous bandwidth will enable simultaneous observation of multiple lines, further improving efficiency and relative calibration accuracy.	Potential use in OST. Needed for future sub-millimeter/FIR suborbital missions (instruments for SOFIA and balloon missions such as Stratospheric Terahertz Observatory, STO and Galactic/Xtragalactic ULDB Spectroscopic Stratospheric Terahertz Observatory, GUSSTO) and for potential small-sat and Explorer missions beyond Herschel. Solar system studies of planetary atmospheres will directly benefit. For Earth observing, FPAs will improve coverage speed and provide small spot sizes with reasonably sized antennas. Far-IR SIG: Heterodyne arrays are used in existing and upcoming SOFIA instrumentation, as well as in planned instruments for OST.	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission PDR anticipated in the mid-2020s. The next round of SOFIA instruments will need to reach TRL 6 by the end of the decade (i.e., 3-5 years). Far-IR SIG: 2-4 years for deployment on SOFIA and balloon-based platforms.

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Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
High-Efficiency Object Selection Technology for UV Multi-Object Spectrometers	Future NASA UV missions devoted to spectroscopy require high-efficiency (> 50%), multi-object spectrometer (> 100 simultaneous sources; R~3000 or greater) architectures and components for operation at 100-400 nm or broader band (e.g., micro-mirror devices, micro-shutter arrays; fiber-fed spectrographs; and integral-field spectrometers).	Digital micromirror devices (DMDs)are at TRL 5, based on European studies for Euclid, and SAT development efforts. Micro-shutters are at TRL 6 from JWST testing (IR) and sounding rockets (FUV), however only for certain form factors and magnetically actuated operation. Next-generation micro-shutters are TRL 3 from laboratory demonstration. Recent advances in high-reflectivity mirror coatings have enabled the adaptation of image slicers from the VIS/IR to the UV for a first far-UV IFS. An APRA sounding rocket instrument in development to bring UV image slicers to TRL 6+ by 2023. Other IFS-enabling technologies, such as reconfigurable analog mirror arrays or UV-transmissive fibers, are TRL 2 or less.	2-6	2	Routinely produce large-format, high-throughput, moderate-resolution systems that can be used in a variety of Explorer, medium, and strategic missions. Key performance criteria for the UV/VIS/IR include: ● Sensitivity over the spectral interval 0.10-1.7 µm, including compatibility with high-reflectivity mirror coatings, if applicable. ● Effective demonstration of rejection of off-axis geocoronal/galactic/interplanetary/astrophysical background and suppression of scattered light from the same sources. ● Source multiplexing without spectral confusion limitations ● Low instrumental background (optical scattering, thermal background, stability of moving parts, repeatability of operation, etc.).	High-performance multi-object spectrometers can increase the science impact of missions by orders of magnitude. Space telescopes today can obtain slit spectra of a single object or slit-less spectra of a field, but not slit spectra of multiple objects in a field, nor can they reconfigure the focal plane (like a fiber fed spectrograph) for integral field spectroscopy in the far-UV. New technologies that would eliminate spectral confusion would enable efficient spectroscopic mapping of extended sources in the UV. Enabling technology for small, wide-field telescopes appropriate for an Explorer mission.	UV/Vis/IR multiplexing technologies have a broad application to astrophysics, heliospheric, and Earth-science missions.	Should come as early as possible since mission definition and capabilities are built around instrument performance. Development for space astronomy is needed in time to respond to an expected announcement of opportunity for an Explorer-class mission in 2021.
High-Performance Spectral Dispersion Component/ Device	Past NASA imaging missions (e.g. GALEX, Swift-UVOT) have demonstrated science enhancement by adding relatively inexpensive transmission spectroscopy modes. Such spectrograph types are also efficient for low spectral resolution surveys. Future missions require enhancements on the current state-of-the-art with higher diffraction efficiency (> 90%) that is uniform over a large range of incident ray angles, enables near-diffraction limited resolution, and features integrated bandpass selecting or order sorting capability to avoid spectral and source confusion.	The current SOTA, such as the NISP slitless spectrometer on EUCLID, achieves 90% efficiency in the center of the FOV, falling to ~70% at the edges where the blaze function deviates from optimum. A corrector is required to achieve the imaging and spectral resolution requirements, adding to the instrument complexity. For the UV, the GALEX and Swift UVOT grisms are both limited to the near UV (> 200 nm).	3	3	The key objectives to enhance the next-generation of slitless spectrometers are: : • Compact enough to be installed in the spectral-filter wheel as one filter element; • Accommodate a large physical size for wife field coverage on large (> 0.5m diameter) telescopes; • Diffraction limited (or nearly so) in the wavelength range; • Relatively high spectral resolution (R > 500); • . Operational bandpass between 600 to 2400 nm with the specific bandpass set by the science requirements of the future mission; • High diffraction efficiency (>95% at peak wavelength) with small efficiency losses (< 5% from peak) at the edges of the FOV; • Compatible with order-sorting and bandpass selecting technologies, such as filter coatings.	The science return for future missions includes dramatically reduced ghost-spectra intensity, increased throughput (transmittance) and sensitivity, and higher efficiency surveys with lower calibration systematics. Development of high efficiency, single optic slitless spectrometers will greatly simplify future instruments, requiring less mass and volume that the current state-of-the-art.	Wide-field or all-sky spectroscopic surveys in the VIS/IR, including Explorer and Probe-class missions. VIS/IR imaging missions where a spectroscopic mode would be science enhancing. Compact, single-element transmission gratings with diffraction limited performance, or aberration correcting freeform profiles could have significant impact on a CubeSat or SmallSat where volume and mass are critical.	TRL 6 demonstration by early/mid 2020's. .

Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
High Reflectivity Broadband FUV-to-NIR Mirror Coatings	General astrophysics and exoplanet science require high-throughput observations between 100 nm and 2.5 μm. Coating should achieve >50% reflectivity at 105 nm while not compromising performance at wavelengths > 200 nm compared to existing state-of-the-art. Coating process must be scalable to meter-class segments and repeatable to ensure uniform performance across an aperture comprised of >100 segments.	Al + enhanced LiF ("eLiF") coatings have been deposited on the SISTINE secondary mirror and will fly on a sounding rocket demonstration in mid-2019 (TRL 6). Protected eLiF coatings (using MgF_2 and AlF_3 overcoats) have been demonstrated on samples and show no appreciable change in the base reflectivity (TRL 3). Additional development is necessary to demonstrate repeatability of the optimal coating prescription, and scalability to meter-class optics.	3,6	3	>50% Reflectivity (100-115 nm) >80% Reflectivity (115-200 nm) >88% Reflectivity (200-850 nm) >96% Reflectivity (>850 nm) <1% Reflectance non-uniformity (over entire primary mirror) over band between 200 – 2000 nm. Develop and optimize the coating process and implement on sub-scale mirror samples. Evaluate and verify coating performance. Repeat coating deposition multiple time (minimum of 3) to verify repeatability. Begin age-testing the sub-scale samples by storing in a controlled environment and subjecting to routine measurements. Follow the sub-scale sample demonstration, coat a full-scale (1-meter-class) mirror and verify coating performance and uniformity. Complete optical, radiation, and environmental qualification testing to bring the Far-UV Broadband Coating technology component to TRL 6. (see LUVOIR final report for more detailed plan, schedule, and cost)	Improved coating reflectivity can have cross-cutting benefits for any missions with broadband UVOIR science. Stable coatings that maintain performance in ambient environments can have programmatic benefits by simplifying I&T and handling procedures.	NWNH noted the importance of technology development for a future ≥ 4-m class UV/Vis mission for spectroscopy and imaging. This technology would also support the next generation of UV missions, including Explorers, Probes, and large (> 4-m apertures) future UV/Optical/IR telescopes, and is key for a LUVOIR Surveyor. All future missions with optics, particularly missions with an important FUV or UV component, will benefit from improved coatings. Benefits will also accrue to planetary, heliospheric, and Earth missions utilizing the UV band.	Per LUVOIR Final Report, TRL 6 prior to Phase A start in 2025 is required. See LUVOIR Final Report for detailed development plan recommendations, schedule, and cost estimate.

Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
High-Throughput Bandpass Selection for UV/VIS	High-throughput bandpass limiting technology with high out-of-band rejection does not exist or exists only in a limited form for UV instruments. Future UV-sensitive NASA missions would greatly benefit from the development of transmissive or reflective UV filters, detector coatings, or other new technologies that would enable high-throughput observations of select, mission specific bandpasses, while limiting background contamination. Efficient Lyman alpha rejection with transmission at less than 1200 angstroms in particular would represent an enabling technology. Narrow band imaging filters with $\Delta\lambda/\lambda$~2-3 % would also represent an enabling technology for the entire UV/VIS/IR. Long-wavelength "red" rejection technologies are required for some detectors for applications in the UV.	Commercial optical filters are mature and widely available for visible and NUV wavelengths (> 250 nm). Current state of the art UV-transmission filters has efficiencies of < 10-20% below 180 nm and < 50% for 180-280 nm. Robust commercial high-efficiency UV-transmitting filter solutions are not frequently available. Red-blocking "Woods filters" with low efficiency (< 10-15%) and lifetime issues have been employed for solar-blind imaging. All dielectric designs are less commonly available at shorter FUV wavelengths due in part to the lack of transparent high-refractive-index materials in this wavelength. Dielectric multi-layer mirror coatings have been developed to TRL 3, with a reflective filter designed to reflect Lyman alpha (not reject) flown on a heliophysics sounding rocket. Photocathode technologies for photoemissive detectors have demonstrated broad band sensitivity and various long wavelength cutoff profiles. Newer photocathode implementations (GaN, blue Bialkali) have steep cutoffs (0.1%) at ~350nm but are not yet fully developed. Application to large areas in potentially straightforward as similar photocathode techniques have enabled 200mm devices. Dichroic filters have been designed for the UV, for example the FUV/NUV split in the GALEX instrument, but efficiency in each channel (50/80%) and effective bandwidth in each channel (< 50 nm) is limited at current SOTA. Metal-dielectric structures have been successfully implemented as bandpass filters for FUV broadband detector systems (e.g., HST, Swift) but with low throughput (< 20% below 200 nm). Similar designs have been implemented in laboratory settings directly on silicon FPAs to provide integrated red rejection capabilities with increased throughput (> 50% below 200 nm).	4	3	Key Objectives: • Filter transmittance in UV for R~5 bandpass filter: > 50% (80%) FUV (NUV); • Red-blocking transmittance: > 50-75% (UV), < 0.0001%-0.01% Vis-NIR; • Dichroic: Mid-UV Split: R (FUV) > 0.8, T (NUV) > 0.9; • Bandwidth: Application specific varies from narrow (20 nm), to wide, e.g. FUV (100 nm), NUV (100nm up to-200 nm); • Minimum wavelength: 100-105 nm; • Improved dielectric designs (dichroics, edge filters); dichroic: UV/Vis Split: R (UV) > 0.9, T (Vis) > 0.9; and Detector-integrated filters (red rejection, narrowband, broadband AR, or bandpass tuning and red rejection photocathodes) on large scale.	High efficiency and low noise resulting from out-of-band rejection, and multi-channel instruments using dichroics allow deep astronomical surveys to be conducted with space-based telescopes on much shorter, feasible timescales, and enable instrument designs that exploit the aperture size (geometrical area) and full working FOV of the telescope. The integration of UV-filtering elements directly on a sensor system has the potential to improve in-band sensitivity while providing out-of-band rejection. Eliminating discrete optical component can reduce instrument complexity. Relevant experience with UV, Vis, and/or NIR filters and dichroics that achieve the technical goals set forth above is essential for maximizing the return of future space observatories. This technology is crosscutting, with applications across astrophysics, planetary, and space sciences. Commercial applications similarly benefit from high throughput and band-rejection. Techniques capable of producing multilayer (metal-dielectrics) ultrathin (10's nm), uniform (~ 1%), low polarization ((~1%), pinhole free layers with sharp well-defined interfaces—such as produced by atomic layer deposition (ALD)—are crucial for producing high throughput band-selecting filters.	COR science requires deep multi-wavelength measurements of galaxies and AGN to study their evolution from the formation of the first stars and black holes to structures observed on all scales in the present-day universe. High priority for observations of unseen phenomena such as the cosmic web of intergalactic and circumgalactic gas and resolved light from stellar populations in a representative sample of the universe. Potentially relevant missions include a LUVOIR space telescope, Explorer and Probe-class missions that can conduct wide-field surveys, and small-sat experiments that can advance technology while addressing one or more COR science objectives. Exosolar planet characterization Time-domain UV observation of transient events such as GW EM counterparts, stellar flaring, and life cycle of stars,	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission PDR anticipated in the mid-2020s.

Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
Large-Format Object Selection Technology for Multi-Object Spectrometers for HabEx	An array of apertures for the UV spectrometer	• 171 × 365 shutters with electrostatic and magnetic actuation (JWST NIRSpec, TRL 7) • 128 × 64 electrostatic actuated array at TRL 4; will fly in FORTIS sounding rocket summer 2019 • 840 × 420 electrostatic, buttable array developmental model with partial actuation 840x420 full array by 2021 via SAT funding	3	3	300 × 300 shutters needed	Engineering improvement to save volume in layout of astrophysics UV spectrometer and save some mass of microshutter arrays; improve reliability of microshutter arrays	HabEx, LUVOIR	Current SAT funding plans TRL 5 by end of FY 2021
Starshade Deployment and Shape Stability	The capability to deploy on-orbit a starshade that is stowed in a launch vehicle fairing to a precise shape, and to maintain that shape precision during all operational environments.	Manufacturing tolerance (≤ 100 μm) verified with low fidelity 6 m prototype and no environmental tests. Petal deployment tests conducted but on prototype petals to demonstrate rib actuation; no shape measurements, no long-duration stowage tests. Petal deployment tolerance (≤ 1 mm) verified with low fidelity 12 m prototype and no optical shield; no environmental testing (Exo-S design).	4	4	A system that will deploy the petals from a launch-stowed configuration to the needed shape (to better than ≤ 1 mm (in-plane envelope) and maintain petal edges to ≤ 100 m (in-plane tolerance profile for a 7 m petal on the 34 m-diameter Exo-S design; tolerances scale roughly linearly with starshade diameter), and be optically opaque.	The capability to stow, survive launch, and deploy the petals and opaque inner disk of the starshade to within the deployment tolerances budgeted to meet the shape, and thus the contrast requirements. The shape must be maintained within a stability envelope to enable imaging and spectroscopy of Earth-like exoplanets.	HabEx, WFIRST/Starshade Rendezvous, other future starshade missions	Risk reduction prior to completion of Astro2020, TRL 6 needed by late 2020's for mid-2030s launch.
Starshade Starlight Suppression and Model Validation	The capability of a starshade to suppress diffracted on-axis starlight and scattered off-axis Sunlight to levels needed to characterize Earth-like exoplanets. The capability to experimentally validate model of the starshade's optical performance at subscale.	Validated optical model with demonstrated 10^{-6} suppression at white light, 58 cm mask, and F (at the starshade tips) = 210; 6×10-6 suppression demonstrated at F =15; 4.6×10^{-8} suppression demonstrated at F ~ 27 Etched amorphous metal edges meet scatter specs integrated in-plane shape tolerance is to be demonstrated.	4	4	Experimentally validate at flight-like Fresnel numbers (F) the equations that predict starshade starlight suppression: total starlight suppression ≤ 10–8 in scaled flight-like geometry, F between 5 and 40 across a broadband optical bandpass. Contrast model accuracy validated to better than 25%. Limit edge-scattered sunlight and diffracted starlight with optical petal edges that also handle any stowed bending strain. Limit solar scatter lobe brightness to better than visual magnitude (V) 25	The starshade must produce the desired starshade shape to within tolerances specified by an error budget to create contrast levels to better than 10^{-10} at the image plane. The precise positioning and manufacture of the starshade edges to minimize the diffraction from on-axis starlight and scatter/diffraction from off-axis Sunlight detected at the science focal plane. The starlight suppression capabilities of the starshade must be demonstrated on the ground to validate optical models and the error budget, which are used to predict performance in a space environment.	HabEx, WFIRST/Starshade Rendezvous, other future starshade missions	Risk reduction prior to completion of Astro2020, TRL 6 needed by late 2020's for mid-2030s launch.

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Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
Stellar Reflex Motion Sensitivity: Extreme Precision Radial Velocity	Capability to measure exoplanet masses down to Earth-mass.	Ground-based RV: state-of-the-art demonstrated stability is currently 28 cm/s over 7 hours (VLT/ESPRESSO). Laser frequency combs demonstrated on ground-based observatories with correct mode spacing, non-NASA work is advancing miniaturization. Fiber laser-based optical frequency combs demonstrated on sounding rocket though with closer line spacing than useful for RV.	2-3	3	Capability to measure exoplanet masses down to Earth-mass. The radial velocity semi-amplitude of a Solar-mass star due to an orbiting Earth-mass planet at 1 AU is 9 cm/s. Technology to make radial velocity mass measurements may include using a space-based instrument to avoid atmospheric telluric lines and simultaneous measurements of stellar lines across a broad band (both Vis and NIR). Stability of the instrument and its absolute calibration must be maintained on long time scales in order to enable the measurement. Theoretical understanding of astrophysical noise sources (stellar jitter) and how to mitigate them.	Interpretation of spectra of Earth-like exoplanets in reflected light requires the measurement of mass.	WFIRST, LUVOIR, HabEx If a need for a precision astrometry mode in LUVOIR is identified, PDR in 2025.	If a need for space-based RV is identified, then ready a PDR in 2025 for an Earth-finder type mission. If ground-based supporting role is identified, then capability is needed by launch in early 2030s.
Stellar Reflex Motion Sensitivity: Astrometry	Capability to measure exoplanet masses down to Earth-mass.	GAIA preliminarily achieved 34 micro arcsecond error but ultimately could achieve 10 microacrseconds on bright targets after all systematics are calibrated SAT/TDEM-funded demonstration (Bendek) of diffractive pupil showed 5.75×10^{-5} λ/D or 1.4 microarcsecond on a 4m telescope (limited by detector calibration) Preliminary study of 1-m space telescope and instrument with in-situ detector calibration can achieve 0.8 micro arcsecond in 1 hr	2-3	3	Astrometric detection of an exo-Earth at 10pc requires 0.1 microarcsecond uncertainty. Technology with the stability needed to make astrometric measurements to this level, possibly requiring detector metrology and/or diffractive pupils Theoretical understanding of astrophysical noise sources (star spots) and how to mitigate them.	Interpretation of spectra of Earth-like exoplanets in reflected light requires the measurement of mass.	WFIRST, LUVOIR, HabEx If a need for space-based RV is identified, then ready a PDR in 2025 for an Earth-finder type mission. If ground-based supporting role is identified, then capability is needed by launch in early 2030s.	If a need for a precision astrometry mode in LUVOIR or HabEx is identified, needed by 2025.

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Gap Name	Description	Current State-of-the-Art	TRL		Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
			SOTA	Solution				
Advanced Cryocoolers	Cryocoolers are required for achieving very low temperatures (e.g., ~4 K) for optics and as pre-coolers for sub-Kelvin detector coolers for COR missions. Eliminating the need for expendable materials (cryogens) will increase achievable lifetime and reduce system mass and volume. Improvements are needed in terms of performance, especially low power consumption and low vibration levels.	For several-Kelvin temperature designs, the current SOTA includes pulse-tube, Stirling, and Joule-Thomson coolers which are at high TRL but are expensive, and do not yet have good enough performance. The SHI cooler used on Hitomi had the necessary cooling power at 4.5 K (Fujimoto, 2018), but the expected lifetime was 5 years rather than the 10 years required for Origins. Changes in the working fluid have been shown to produce temperatures in the 4.5 K range as required for Origins. Low vibration levels have been achieved by the miniature turbo-Brayton cryocooler of Creare down to 8 K. A currently funded SBIR Phase II will extend this operation to 4 K. DoD has some interest in these 4 K cryocoolers as well.	3-6	4	Several mission concepts require sustaining temperatures of a few Kelvin, with continuous heat-lift levels of a few dozen to ~200 mW at temperatures ranging from 4 to 18K. Other concepts could benefit from greater heat lifts at somewhat higher temperatures. All this needs to be accomplished with < 9000 W/W input power/cooling power at 4.5 K. Such coolers need to be compact, and impose only low levels of vibration on the spacecraft. In some applications, a sub-Kelvin cooler will be implemented, and an advanced few- Kelvin cryo-cooler able to maintain the sub-Kelvin cooler's hot zone at a steady (e.g.) 4.5 K will be very beneficial.	Cryocoolers able to operate near 4 K, cooling detectors and optics directly, as well as serving as a backing stage for ultra-low-temperature (sub-Kelvin) coolers will enable large FIR telescopes, as well as ultra-low-noise operation of cryogenic detectors for other bands. Increased heat lift, lower mass, lower volume, increased operational lifetime, and reduced cost will enable such missions to fly extended durations without wasting critical resources on cooling. Large-capacity cryocoolers are required to achieve astrophysical photon-background-limited sensitivity in the FIR and meet sensitivity requirements to achieve the science goals for future FIR telescopes or interferometers.	This technology is a key enabling technology for any future FIR mission, including OST. It is also applicable to balloons, airborne platforms, Explorers, and Probes. For example, it would improve performance of STO2 long/ultra-long duration balloon and SOFIA instruments. Explorer missions would also be very positively impacted. Low vibration cooling would open up other wavelength missions, such as LUVOIR, to use of sensitive cryogenic detectors.	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission PDR anticipated in the mid-2020s.
High-Performance, Sub-Kelvin Coolers	Optics and detectors for FIR, sub-millimeter, and certain X-ray missions require very low temperatures of operation, typically in the tens of milli-Kelvins. Compact, low-power, lightweight coolers suitable for space-flight are needed to provide this cooling. Both evolutionary improvements in conventional cooling technologies (adiabatic demagnetization and dilution refrigerators) with higher cooling power, and novel cooling architectures are desirable. Novel cooling approaches include optical, microwave, and solid-state techniques.	Existing adiabatic demagnetization refrigerators with low cooling power (0.4 μW) at 50 mK are at TRL 7-9 (Hitomi/SXS) (Shirron, 2015)but high-cooling-power versions (6 μW) are at TRL 4. (Shirron, 2000) Low cooling power (<1μW) dilution refrigerators (Collaudin, 1999) and ultra low (<0.1 μW) solid-state cooling approach based on quantum tunneling through normal-insulator-superconductor (NIS) junctions are both at TRL 3. Currently funded technology development is expected to result in a TRL 5 or 6 ADR for use over the temperature range of 10 to 0.050K with high efficiency and cooling power of 6 micro-W at 0.05 K. (Tuttle, 2017) Further development, extending the low temperature to 35 mK while maintaining the 6μW cooling capability would be enhancing.	4	4	A sub-Kelvin cooler operating from a base temperature of ~4 K and cooling to 50 mK with a continuous heat lift of 6 μW at 50 mK is required. To enhance detector sensitivity, cooling to 35 mK with 6 μW of cooling power is enhancing. Features such as compactness, low input power, low vibration, intermediate cooling, and other impact-reducing design aspects are desired.	Sub-Kelvin cryocoolers are required to achieve astrophysical photon-background-limited sensitivity in the FIR and high-resolution sensitive X-ray microcalorimetry. Techniques to lower cooling costs and improve reliability will aid the emergence of powerful scientific missions in the FIR and X-ray.	This technology is a key enabling technology for any future FIR mission, including OST. Sensors operating near 100 mK are envisioned for future missions for X-ray astrophysics, measurements of the CMB, and FIR imaging and spectroscopy. Applicable to missions of all classes (balloons, Explorers, Probes, and flagship observatories). High synergy with X-ray missions using microcalorimeters.	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission PDR anticipated in the mid-2020s.

2019 Astrophysics Strategic Technology Gaps

Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
Large Cryogenic Optics for the Mid IR to Far IR	Large telescopes (of order 10 m in diameter) provide both light-gathering power to see the faintest targets, and spatial resolution to see the most detail and reduce source confusion. To achieve the ultimate sensitivity, their emission must be minimized, which requires these telescopes to be operated at temperatures (depending on the application) as low as 4 K. Sufficient thermal conductivity internal to the telescope segments (> 2W/m K) is required to isothermalize the primary. Key technologies to enable such a mirror include new and improved: • Mirror substrate materials and/or architectural designs • Processes to rapidly fabricate and test cryogenic mirrors • Mirror support structures that are stable at the desired scale • Mirror support structures with low-mass that can survive launch at the desired scale Also needed is ability to fully characterize surface errors and predict optical performance via integrated STOP (structure thermal optical performance) modeling. These telescopes will probably need in-orbit adjustability and should be designed for low-cost optical-performance verification before launch. Some material properties, such as damping for telescope structures, are also needed.	JWST Be mirror segments meets Origins requirements now, so TRL 5 with a heavy (~ 68 kg/m^2 including support structure) technology; TRL 3 exists for other materials like SiC. Cryogenic low-dissipation actuators exist at TRL 3-5. The MMSD program has produced 1.35-m JWST class SiC actuated hybrid mirror segments with < 14 nm rms surface figure error, < 10 Å micro-roughness (projected), and < 25 kg/m² total. This technology is at TRL5. The 3.5-meter SiC Herschel Primary Mirror meets all requirements except diffraction limited performance. The Herschel primary mirror is diffraction limited at 80 micrometers. Herschel SiC mirror technology is TRL 9. The balloon BLAST program is developing a 2.5-meter Carbon Fiber Resin Epoxy (CFRP) or Graphite Composite mirror. Apertures of up to ~10 meters are undergoing ground-based tests, including the phase 1 study for the Large Balloon Reflector.	5	4	Develop a feasible, affordable, and low mass (target 35 kg/m² including support structure) approach to producing a 6-m-class telescope with sufficiently high specific stiffness, strength, and low areal density to be launched; while maintaining compatibility with cryogenic cooling and FIR surface quality/figure of ~1µm rms. Use of materials and techniques that do not require cryo-null figuring is required. Material property measurements at cryogenic temperatures for structures and optics such as damping, emissivity, thermal conductivity, etc. Development is required to fabricate components and systems to achieve the following: • Monolithic: 1 to 4 meters • Segmented: > 4 meters • Surface Figure: < 150 nm RMS AT TEMPERATURE • Cryo-Deformation: < 100 nm RMS (surface) • First Mode Frequency: >200 Hz per segment • Areal Cost: < 2M$/m² Areal Density: < 35 kg/m²	Low-cost, lightweight cryogenic optics at reasonable cost (~2M$/m²) are required to enhance development of large-aperture FIR telescopes in the 2020s. Large apertures are required to provide the spatial resolution and sensitivity needed to follow up on discoveries from the current generation of space telescopes. A high altitude, long duration observing platform with a mirror factors of 2-5 larger than on either SOFIA or Herschel has the potential to increase sensitivity in the far-infrared by factors of several in particular wavelength regimes over either facility, at relatively low cost. This enables scientific breakthroughs in the far-infrared including (1) detecting the dusty progenitors to `ordinary' local galaxies at redshifts up to z=3, and (2) high sensitivity mapping of debris disks around young stars. This technology is also relevant to e.g. Earth observation.	This is an enhancing technology for any future single-aperture FIR telescope, and an enhancing technology for a FIR interferometer. This technology development will enable (current) MIDEX-class science with a SMEX, Astrophysics Probe-class science with a MIDEX, and more ambitions larger-mission science with an Astrophysics Probe-class implementation. Development of inexpensive 1-3-m monolithic lightweight stiff mirrors will benefit suborbital, Explorer, and Astrophysics Probe missions. This technology is of particular relevance to ultra-long duration balloon projects, which are maturing as a viable and attractive platform for multiple astrophysics missions.	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission PDR anticipated in the mid-2020s.

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Long-Wavelength-Blocking Filters for X-Ray Micro-calorimeters	A new generation of filters is needed to block undesirable photons being incident on an X-ray microcalorimeter array that has greater transmission in the soft X-ray energy band of 0.2-1.0 keV. A stack of these filters, located at various temperatures, need to be able to block optical, UV and infra-red photons from being absorbed in the X-ray microcalorimeter array. They need to be optimized to be as thin as possible in order to optimize the transmission at low energies, allowing the increase in transmission by more than an order of magnitude at 0.2 keV. The use of optimized micro-machined meshes will allow the mechanical support and high throughput.	Blocking filters of the general type have successfully flown on Hitomi, and thus the SOTA is designated TRL-9. For Lynx, higher transmission is desired for soft X-rays requiring thinner aluminum and polyimide, thinner than has so far been developed or demonstrated. The filters also need to be significantly larger (> 6 cm). Thus for the full solution, the TRL is listed at TRL-3, with the principle having been demonstrated experimentally. The waveguide cut-off filter option has been demonstrated for 15 micron holes, but not at small enough holes for this application (~1-2 microns).	9	3	Large area (>6 cm) films supported by fine meshes, as thin as 10 nm of aluminum, and 20 nm of polyimide. Another approach is the use of wave-guide cut-off filters that have no films between a support mesh, with extremely tiny holes (~1-2 microns across).	Having more than an order of magnitude transmission available for the softest X-ray makes more of the collecting area of the X-ray optic available for science. The X-ray optic would have a corresponding order of magnitude more area for some scientific measurements. Measurements include observations of highly redshifted sources such AGN and baryons from distant groups of galaxy clusters.	Lynx. The technology is also synergistic with an enabling technology for the US contribution to Athena.	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission PDR anticipated in the mid-2020s.
Low Noise, High QE, UV Detectors	Low-noise detectors for general astrophysics as short as 115 nm	QE 44% 0.115-0.18 µm with alkali photocathode, 20% with GaN; dark current ≤0.1–1 counts/cm2/s with ALD borosilicate plates The individual component technologies for photocathode material, microcapillary array, and readout convertor have been demonstrated. To achieve TRL 5, one device using all 3 desired components must be fabricated and demonstrate performance. HabEx would mature the MCP at the required 100 mm x 100 mm format size	4	4	• Dark current <0.001 e-/pix/s (173.6 counts/cm2/s), in a space radiation environment over mission lifetime, High QE for 0.115–0.3 µm wavelengths	Enables astrophysics UV spectrograph field of view and sensitivity requirements.	HabEx, LUVOIR	

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Low Stress, Highly Stable X-ray Reflective Coatings	Lynx requires a light-weight X-ray telescope with large collecting area and ~0.5 arc-second angular resolution. The X-ray mirrors used to construct the Lynx telescope will comprise thin, curved substrates (either segmented or full-shell) coated with X-ray reflective thin films. The thin-film coatings must provide high reflectance over the Lynx energy band, and must maintain or improve the high-frequency surface roughness of the substrate (to minimize losses due to X-ray scattering.) Additionally, and crucially, coating stress must be minimized and stabilized, and remaining stress must be compensated in order to mitigate stress-driven substrate deformations that degrade angular resolution. Coating stress must be temporally stable to high precision, including in response to environmental drivers such as thermal cycling.	Iridium single-layer, and boron-carbide/iridium bilayer films, both have been demonstrated to have high X-ray reflectance over the Lynx energy band. Additionally, preliminary work on more complex Ir-based multilayer coatings has demonstrated even better X-ray performance. However, all these coatings have exceedingly high stress when deposited under sputtering conditions that give high film density and low surface roughness, and thus maximal X-ray reflectance performance. Ir-based coatings having low net stress (as measured on flat test substrates) have been demonstrated through various methods. However, preservation of figure error on curved, thin mirror segments has not yet been demonstrated at the 0.5-arcsecond-level. (Chandra substrates are ~50x thicker than those required for Lynx, so Ir coating stress did not degrade angular resolution in that case.) Additionally, coating thickness uniformity better than 2% in two-dimensions on shell segments has not yet been demonstrated, and almost certainly will be required to achieve acceptable figure preservation. Advancement to TRL 4 will require demonstration of X-ray reflective coating deposition on thin, curved substrates (segmented or full-shell) with acceptable figure preservation, demonstration of preservation (or improvement) of high-frequency substrate surface roughness, and demonstration of acceptable X-ray reflectance, using techniques that are scalable for mass production.	3	3	Thin-film coatings deposited onto figured, thin-shell substrates that (a) provide high X-ray reflectance up to 10 keV, (b) have low high-frequency surface roughness (to minimize losses due to X-ray scattering), and (c) preserve the underlying substrate figure after coating deposition to minimize and stabilize coating-stress-driven substrate deformations that degrade angular resolution. Coating deposition and stress compensation methods must be scalable for mass production.	High X-ray reflectance and low surface roughness are needed to achieve high telescope collecting area. Without the development of effective methods to mitigate coating-stress-induced substrate deformations, sub-arcsecond telescope resolution will not be possible using thin-shell mirror substrates.	Lynx	Named missions: Lynx Development needed for 2020 Decadal: Yes Other drivers: Explorer, Probe, and Suborbital-based opportunities.
Photon Counting Large-format UV Detectors	Low-noise detectors for general astrophysics as short as 100 nm	Delta-doped EMCCDs: Same noise performance as visible with addition of high UV QE ~60–80% in 0.1–0.3 µm, dark current of 3×10-5 e-/pix/s beginning of life. 4k×4k EMCCD fabricated with reduced performance. Dark current <0.001 e-/pix/s, in a space radiation environment over mission lifetime, ≥4k×4k format fabricated, updated design for cosmic ray tolerance is under test, high QE for 100–350 nm wavelengths WFIRST maturation on EMCCDs has increased radiation tolerance and demonstrated adequate read noise; however delta doping is not planned for WFIRST.	4	4	• Dark current <0.001 e-/pix/s, in a space radiation environment over mission lifetime, • 4k × 4k format for starshade UV spectrometer (Enabling for HabEx) • ≥4k × 8k format for UV spectrograph astrophysics camera (Enhancing for HabEx) • QE > 60% for 0.1–0.3 μm wavelengths	Improves dark current at all wavelengths, particularly in the UV. For the starshade UV spectrometer, the 4k x 4k format size is enabling for the science spectral bandwidth. For the 4k x 8k format, the delta doped EMCCDs are an alternate to MCPs	HabEx, LUVOIR	A funding start in 2022 could result in TRL 5 by mid 2023.

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			SOTA	Solution				
Polarization-Preserving Millimeter-wave optical elements	High-throughput telescopes and optical elements with controlled polarization properties are required for the IP. These require development of cryogenic mm-wave filters and coatings. Measurement of CMB polarization on large scales may require rapid polarization modulation to separate sky-signal polarized intensity from instrumental effects. Employing modulators large enough to span the telescope primary aperture is an advantage in that sky polarization can be separated from instrumental effects.	Single-layer anti-reflection (AR) coatings are in widespread use. Meta-material AR structures are in development and early use. Several experiments in the field are currently using rapidly spinning half-wave plates as the primary means of modulating the signal and separating it from longer time variations. More experiments are coming online using both half-wave plates and variable-delay polarization modulators that endeavor to measure larger areas of the sky. Pressed metal-mesh filters are in widespread use, which require anti-reflection coatings that limit filter bandwidth. Large-scale filters have been demonstrated on ground-based and balloon-borne instruments.	2-5	3	Develop robust multi-layer coatings for broadband applications for commonly used dielectrics (e.g., silicon, alumina, and sapphire). Develop thermal filtering technologies suitable for large Focal-Plane Arrays (FPAs) operating at sub-Kelvin temperatures, using low index of refraction materials to enable filters with high transmission and low ripple over a broad passband. Develop space-compatible modulators, including work on frequency-selective surfaces and mechanisms compatible with the space radiation environment. Minimizing dielectric cross-section to low-energy electrons is a priority. Develop and compare strategies for instrument architectures with and without rapid modulators. A secondary goal is to ensure that the technology can be implemented in a cost-effective way for large optical elements. Large in this context is up to 100 cm in diameter.	Broadband optics can reduce the necessary focal-plane mass and volume for CMB polarization measurements. This may open options for compact optical systems appropriate for lower-cost Explorer opportunities; an international mission concept using broadband refracting optics is in the planning stages. Modulators are potentially a key enabling technology High transmission optics increase per-detector sensitivity.	IP, Far-IR, Explorer, and international experiments to study CMB polarization and absolute spectrum.	**Named missions:** IP (2020s) **Development needed for 2020 Decadal:** Yes, IP **Other drivers:** IP technology development is a NWNH priority that was recently revisited by the mid-Decadal review. International and Explorer implementations of the IP have proposed launch dates during the second half of the next decade.
UV Coatings	Mirror coatings allowing broadband performance into the UV while maintaining high reflectivity and low polarization aberrations over a broad band.	Al coating with combination of MgF_2, LiF, and/or AlF_3 overcoat: 90-120 nm: < 50% reflectivity 120-300 nm: 85% reflectivity 300 nm-2 μm: > 90% reflectivity Polarization differences between orthogonal polarization states, uniformity, and durability of coatings on large optics is unknown. Flight: HST uses MgF_2; 85% reflectivity λ> 120 nm; 20% reflectivity λ < 120 nm			Mirror coatings that enable high reflectivity to wavelengths as short as 90 nm while maintaining good performance in Vis/NIR band. Coating uniformity must be good enough that polarization phase and amplitude difference < 1% between orthogonal polarization states across the whole wavelength band.	Enables a telescope to have both sensitivity to UV and keep polarization aberrations at all wavelengths at a level commensurate with coronagraphy.	HabEx, LUVOIR	Demonstration of feasibility and as much risk reduction as possible prior to completion of Astro2020. Per LUVOIR and HabEx Final Reports, TRL 6 in the mid-2020's would be needed.
UV Detection Sensitivity	The sensitivity to perform imaging spectroscopy of exoplanets in the ultraviolet.	<u>Lab</u>: Micro-channel Plates (MCP): 0 read noise, 90 – 300 nm, spurious count rate 0.05 - 0.5 counts/cm^2/s; QE 20-45%; resolution element size 20 □m. EMCCD: 0 read noise, dark current > 0.005 e-/res/hr; QE 30-50%; resolution. el. size 20 μm <u>Flight</u>: HST HRC: In relevant UV band (250 nm): QE 33%, read noise 4.7 e-, dark current 5.8×10^{-3}, 1024×1024 format			Low-noise ultraviolet (200-400 nm) detectors to characterize exoplanets with an imaging spectrograph. Read Noise: 0 e-; Dark Current: 0 e- /resolution/s; Spurious Count Rate: < 0.05 counts/cm^2/s; QE: 75% ; Resolution size ≤ 10 mm; Tolerant to space radiation environment over mission lifetime.	Enables UV coronagraphy.	HabEx, LUVOIR	Demonstration of feasibility and as much risk reduction as possible prior to completion of Astro2020. Per LUVOIR and HabEx Final Reports, TRL 6 in the mid-2020's would be needed.

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UV/Opt/NIR Tunable Narrow-Band Imaging Capability	High throughput UV, Optical and Near Infra-red narrow-band filters ($\Delta\lambda/\lambda$~2-3 %) with continuously selectable central wavelength capable of covering an un-vignetted and un-aberrated FOV of several arcmin (linear size) or better.	A Tunable Filter in the NIR (Fabry-Pérot etalon with piezo electric actuation) was developed for JWST. The design advanced capabilities beyond existing ground based operational systems to provide low-order gap, very wide waveband, and operation in a cryovacuum environment. However, difficulties occurred in providing a stable and predictable gap separation after exposure to vibration, shock, and cryogenic cycling and was not successfully qualified for flight. The JWST development did not investigate performance down into the lower UV-Vis wavelengths. Space environment challenges with the tunable Fabry-Pérot etalon for the JWST fine guidance sensor. Available from: https://www.researchgate.net/publication/258718456_Space_environment_challenges_with_the_tunable_Fabry-Perot_etalon_for_the_JWST_fine_guidance_sensor [accessed Jul 4, 2017].	3	3	High throughput UV, Optical and Near Infra-red narrow-band filters ($\Delta\lambda/\lambda$~2-3 %) with continuously selectable central wavelength capable of covering an un-vignetted and un-aberrated FOV of several arcmin (linear size) or better.	The availability of variable narrow band filters at UV, Optical and Near Infrared wavelengths will enable systematic studies of a broad range of astrophysical problems in galaxy evolution that are core to the Cosmic Origins program that currently can either not be done or are done very sub-optimally (with grism/slitless spectroscopy, which partially destroys spatial information) or can only be done in few, very lucky cases when the targeted emission line is fortuitously redshifted to the wavelength of available onboard fixed filters.	Tunable narrow band filters will allow us to study the formation and evolution of the proto-cluster environment, the proto-galaxy environment and star-formation in the cosmic web. The device will enable high-angular resolution, large-scale spatial tomography of line-emission processes from galaxies, globular clusters and gaseous nebulae in general. This capability is key, and currently unavailable to address a broad range of problems, from spatial reconstruction of the cosmic web, to satellite star-formation and quenching in massive halos, to the formation of globular clusters, to gas accretion and expulsion in galaxies. These physical processes are key to the Cosmic Origins program and currently cannot be addressed in a systematic way.	

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Warm Readout Electronics for Large-Format Far-IR Detectors	Readout schemes compatible with cryogenic multiplexing and room temperature ADCs and RF electronics for these arrays need to be developed. The cryogenic electronics are covered in a separate gap.	Room temperature readout of cryogenic amplifier outputs currently use FPGAs and ADCs for bandwidths up to 4 GHz having power dissipation of about 50W per channel. Dedicated ASICs would potentially lower the input power requirement by a factor of 10. Origins has baselined using a rad-hard version of a commercial RFSoC using about 50 W per channel, currently at TRL 4.(**enabling for Origins**) Raising to TRL 6 requires using rad-hard parts. (**enhancing for Origins**)	4	4	Using current technology with rad-hard parts is enabling. Recovering the signal to noise with lower-power room-temperature electronics needs to lower the input power by up to a factor of 10. ASIC development takes time and money.	Sensitivity reduces observing times from many hours to a few minutes (≈ 100× faster), while array format increases areal coverage by ×10-100. Overall mapping speed can increase by factors of thousands. Sensitivity enables measurement of low-surface-brightness debris disks and protogalaxies with an interferometer. This is enabling technology. Suborbital and ground-based platforms can be used to validate technologies and advance TRL of new detectors.	FIR detector technology is an enabling aspect of all future FIR mission concepts, and is essential for future progress. This technology can improve science capability at a fixed cost much more rapidly than larger telescope sizes. This development serves Astrophysics almost exclusively (with some impact on planetary and Earth studies).	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission PDR anticipated in the mid-2020s.
Compact, integrated spectrometers for 100 to 1000 µm **(Enhancing)**	Compact, integrated spectrometers operating in the 100 µm to 1 mm band which can provide a wide (e.g., 1:1.6) instantaneous bandwidth at resolving power ($R = \lambda/\Delta\lambda = \nu/\Delta\nu$) ~500 with high efficiency in a compact (~10 cm) package that could be arrayed in a focal plane to provide integral-field mapping or multi-object spectroscopy capability. Si immersion technology can provide increased spectrometric capability ($R \sim 1\times10^5$) with smaller size (factor of 3) over standard Echelle gratings.	Multiple compact spectrometers are under development: including compact silicon gratings and grating analogs, as well as superconducting filter banks. These systems are promising, and in some cases are approaching photon-noise limited performance suitable for ground-based observations, but have not yet been demonstrated in a scientific application.	3	3	An integrated spectrometer + detector array system would demonstrate 1:1.7 bandwidth (or greater), high efficiency (>50%, including detector absorption), resolving power > 400, and a coupling scheme compatible with a telescope beam e.g., an f/4 Gaussian beam. To enable the observatories with hundreds of spectrometers, a single spectrometer + detector array would be a packaged on a silicon wafer on order tens of square cm in size (i.e., less than one 4” wafer).	Large-format spectrometers in the far-IR through millimeter enable 3-D spatial-spectral surveys over large areas. The combination of large spatial coverage (many to tens of square degrees) and spectral bandwidth (giving redshift, or line-of-sight distance) will simultaneously find galaxies and measure their redshifts in large numbers (e.g., on order millions with Origins). This measurement addresses key questions in galaxy evolution and the reionization epoch. This is enabling technology.	Compact spectrometers would greatly reduce the system mass for future far-IR flagship such as Origins, but they also enable interim opportunities such as involvement with SPICA, balloon-borne far-IR experiments which are being proposed, and SOFIA.	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission PDR anticipated in the mid-2020s.

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Optical-blocking filters (OBF)	Future EUV and X-ray missions will have large effective area optics and silicon based detectors on the focal plane. These large X-ray optics will focus optical photons as well as the photons of interest, causing the silicon based detectors to be swamped by an optical photon background, deteriorating their signal-to-noise performance. Future missions will require a method of attenuating this optical background while optimizing the effective area of the instruments for the target photon energy. The method used to attenuate the optical photons needs to offer high transmission of the target photons, good optical photon attenuation, high throughput, and relative immunity to contamination issues. This will allow these future missions to realize their maximum effective area performance, which will lead to high scientific yield.	Current state-of-the-art filters fall into two categories. Directly deposited OBFs are deposited onto the surface of the detector. They can be thin and don't require a support structure, but are as cold as the detectors. Contaminants in the payload are attracted the coldest surface, so a cold filter will not prevent detector contamination buildup. Directly deposited filters have been used on RGS on XMM-Newton (TRL 9) and examples suitable for future EUV and X-ray missions, are currently under development (TRL 5). • Ryu, K. K. et al. Development of CCDs for REXIS on OSIRIS-REx. Proc. SPIE **9144,** 91444O (2014). • Bautz, M., et al. Directly-deposited blocking filters for high-performance silicon X-ray detectors. Proc. SPIE **9905,** 99054C (2016). • Brinkman, A. C. et al. The Refection Grating Spectrometer on board XMM. in SPIE EUV, X-ray and Gamma Ray Instrumentation for Astronomy **2808,** 463–480 (1996). • den Herder, J. et al. The reflection grating spectrometer on board XMM-Newton. Astron. Astrophysics. **365,** L7–L17 (2001). • Pollock, A. M. T. Status of the RGS Calibration. XMM-Newton Users Group, European Space Astronomy Centre, Villanueva de la Canada, Madrid, Spain (2008). doi:10.1002/hed.21900 • Chandra X-ray Observatory. HRC Calibration Information. HEX IPI Team, CXC Calibration Team, cfa Harvard (2014). At http://cxc.harvard.edu/cal/Hrc/detailed_info.html#uvis_trans Free-standing filters are held in-front of the detectors. This removes them from the detector so they can be warm (reducing contamination issues). However, they require a support structure, often have a polyimide structure to support the blocking material, and are thicker than directly deposited filters (>100 nm Al) which all affect instrument effective area. Free-standing filters have been used on Chandra, XMM-Newton, and Hitomi (TRL 9), but filters on highly transmissive frames are at TRL 4 or 5. • McCammon, D. et al. The X-ray quantum calorimeter sounding rocket experiment: Improvements for the next flight. J. Low Temp. Phys. **151,** 715–720 (2008). • Takahashi, T. et al. The ASTRO-H Mission. in SPIE Space Telescopes and Instrumentation **7732,** 18 (2010). • Koyama, K. et al. X-Ray Imaging Spectrometers (XIS) on Board Suzaku. Publ. Astron. Soc. Japan **59,** 23–33 (2007). • Chandra X-ray Center. The Chandra Proposers' Observatory Guide. Chandra Project Science, MSFC Chandra IPI Teams, Version 14.0 (2011). http://cxc.harvard.edu/proposer/POG/html/chap6.html • Gastaldello, F. et al. Status of the EPIC thin and medium filters on-board XMM-Newton after more than 10 years of operation : II - analysis of in-flight data. in Proceedings of the SPIE **8859,** 885914 (2013). The full solution technology is based around lithographic support meshes that have a high transparency (>90%) and thin Al films (50 nm). They are a new technology that has had minimal testing and so has a TRL of 3.	5	2-3	Optical blocking filter technology needs to be advanced along both categories of filters. Directly deposited OBFs have, to date, consisted entirely of a thin film of Al deposited on the back surface of a Si sensor. There are complex trade-offs between optical blocking and X-ray transmission for other filter materials, but these have not been fully explored because of the chemical and electrical effects that metal deposition has on the back-surface of pixellated Si sensors. Investigation of direct deposition of thin films of Ti, W, and other materials onto Si sensors needs to be undertaken to truly optimize soft X-ray sensitivity and minimize optical contamination. Alternatively, free-standing filters that can be thin enough to compete with directly deposited filters (50 nm or thinner), with a structure that supports the filter film that is better than 90% transparent also need to be explored. This structure would have to be strong enough to survive launch vibrational loads and the thermal cycling environment that would be expected in a space mission. The filters would have to have a high X-ray transmission over the 150 eV to 2 keV energy range, while maintaining a good optical attenuation performance. The requirement would be >40 % X-ray transmission above 200 eV and >10% X-ray transmission below 200 eV. The optical attenuation at a thickness of 50 nm should be 10^{-3}. It would also be advantageous to have the ability to control the temperature of the filters so that any contamination that did build-up on them could be removed through heating.	The potential benefit of advanced filter technology is significantly greater effective area of the instrument, below 2 keV through high X-ray transmission. This will increase the potential scientific yield of the spacecraft. The signal-to-noise performance of the instrument can be optimized by limiting the amount of optical photons that would be able to reach the detectors without affecting target photon energy throughput. Contamination build-up can be controlled by free-standing filters as they can be thermally isolated from the detectors and so can act as a warm barrier between the cold detectors and the hydrocarbon contamination within the payload. Free standing filters allow multiple filter foil thicknesses to be included in an instrument on a filter wheel, optimizing filter characteristics for a particular observation.	Advances in OBF technology will be applicable to any missions that use detectors on the focal plane that are sensitive to optical photons but that target photons in the EUV to soft X-ray bandpass (50 eV to 2 keV). This would include missions such as Lynx that has a large effective area optic and an imaging camera on the focal plane that would be silicon based. Effective optical blocking filters will allow the signal-to-noise of the detected photons to be maximized by attenuating optical photons, while maximizing effective area with highly X-ray transparent filters.	Filter technologies for Lynx will have to be identified in the early 2020s. Filters will also be required in any future X-ray spectrograph, either for grating readouts, imaging readouts, or calorimeter filters. Many future mission concepts (observatory class and probes) will emphasize high-redshift science where maximizing the instrument response below 0.5 keV will optimize the sensitivity.

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Rapid readout electronics for X-ray detectors	Future NASA X-ray missions in both the long term (Lynx, which is endorsed by Enduring Quests Daring Visions Report and currently under STDT study) and nearer term (Probe and Explorer-class opportunities), as well as the Athena mission, led by the European Space Agency (ESA), will have focal-plane instruments that have many pixels (> 10 Mpix) and very fast frame rates. A key technology that will need further development to support these focal planes will be electronics boards that can read out and process the events from these detectors at very rapid rates.	The concept for a board that would accomplish the requirements for both JANUS and Athena was initially developed when JANUS was in a phase-A study and Athena had a potential opportunity for US contribution to these electronics. The need still exists for such a board for other future missions such as Lynx, Arcus, or other upcoming Explorer and/or Probe-class missions. A design was developed using a Xilinx Field Programmable Gate Array (FPGA) and parallel event processing that enables the required speeds. A prototype board was built, with firmware being finalized. Current TRL is assessed by the team as 4, and planned to be at TRL 5 in summer 2017.	4-5	4-5	Development of digital electronics that can accept data and detect and characterize X-ray events at rates required by Lynx (> ~ 100 Mpix/s)	Enable rapid detector readout and event characterization for a variety of possible X-ray missions, large and small: flagship, Probes, Small Explorer (SMEX), Medium-class Explorer (MIDEX), and CubeSats. In particular, this will enable missions such as Arcus, which is being proposed, and/or Lynx, which is endorsed by Enduring Quests Daring Visions and under study by an STDT in preparation for the 2020 Decadal Survey. It would also be useful for other possible missions such as probe-class missions like TAP or AXIS; SMEX and Explorer like Arcus; and even CubeSat opportunities. These developments could also contribute to efforts by our European colleagues on technology needed for the Athena mission.	Lynx (currently under study by a NASA STDT as a large strategic mission concept) is one example of a potential mission requiring rapid readout electronics with these characteristics (Kouveliotou et al. 2014, "Enduring Quests, Daring Visions;" & Vikhlinin et al. 2012 gives a possible strawperson example of how this mission might look). The large-FOV instrument on this mission specifically required large-format APS. This instrument would provide a large FOV with excellent spatial and temporal resolution and moderate spectral resolution. The heart of the instrument is a > 16 Mpix focal plane with a readout requirement of >100 frames/second and is comprised of an array of X-ray photon-counting APS. Similar requirements would apply to any other similar mission that couples large effective area with a need for large-format/many-pixel detectors, or missions that require rapid readout of many pixels for other purposes such as timing resolution or background suppression. Examples: Lynx, Arcus, Athena, Probe-class X-ray missions with more targeted capabilities, JANUS-like missions, XTiDE-like missions.	**Named Missions:** Lynx and Athena (2020) **Development needed for 2020 Decadal:** Yes **Other drivers:** to ready this technology for a future mission that could begin development as early as 2018, technology design and testing would need to achieve TRL 5/6 between 2018 and 2035, depending on specific mission.

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Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
Short-Wave UV Coatings	Allows astrophysics imaging as low as 0.1 µm	For a 0.1 µm cutoff, Al + LiF + AlF3 has been demonstrated at the lab proof-of-concept level with test coupons achieving reflectivities of 80%+ for >0.2 µm and 60% at 0.1 µm and 3-year lab environment stability	3	3	• Reflectivity from 0.3–1.8 µm: >90% • Reflectivity from 0.115–0.3 µm: >80% • Reflectivity below 0.115 µm: >50% • Operational life: >10 years Development performance on cm size blanks needs to scale to meter class. Durability is critical with accelerated lifecycle tests taking 1-3 years.	Improves astrophysics science output for UVS	HabEx, LUVOIR	Demonstration of feasibility and as much risk reduction as possible prior to completion of Astro2020. Per LUVOIR and HabEx Final Reports, TRL 6 in the mid-2020's would be needed.
Advancement of X-ray Polarimeter Sensitivity	Standard photoelectric X-ray polarimeter designs are both quantum-efficiency (QE) -limited and challenging to calibrate due to diffusion of electron signal as it drifts through the gas. Drifting negative ions decreases diffusion to the thermal limit, thereby decoupling sensitivity from drift distance, and enabling larger detector areas that can be at the focus of larger-diameter mirrors and single-reflection concentrator. Negative-Ion Time-Projection-Chamber (NITPC) polarimeters also allow the selection of constituent gases and pressures to be based on optimization of modulation and QE rather than diffusion properties. This versatility enables a large improvement in sensitivity without driving cost and with only moderate increase to mass and power of the detector and/or instrument. Furthermore, the energy band will be tunable to maximize science return.	Several photoelectric polarimeter concepts such as Polarimeter for Relativistic Astrophysical X-ray Sources (PRAXyS, previously Gravity and Extreme Magnetism Small Explorer, GEMS), Imaging X-ray Polarimeter Explorer (IXPE), and Polarimetry of Energetic Transients (POET) etc. were proposed in 2014 to provide the next substantial step exploiting X-ray polarization to answer key scientific questions for some of the brightest sources in the sky. However, proposed measurements remain photon-limited and the need for higher-sensitivity polarimeters for both faint persistent sources such as Active Galactic Nuclei (AGN) and bright transient sources such as Soft-Gamma Repeaters (SGRs) by way of Explorer missions and probe-class missions in the next decade remains critical. The goal of this development is to make practical the technology that will provide an order-of-magnitude improvement in polarization sensitivity over current-generation instruments.	4		Development of gas electron multipliers optimized for negative ion gas. Development of finer-pitch strip readouts to improve the sensitivity at lower energies and higher pressures. Optimization of gas mixtures to maximize sensitivity (QE vs. track length). Demonstrate lifetime of gas and detector materials is commensurate with mission requirements.	These developments will allow a factor-of-10 improvement in sensitivity without decreasing the sensitivity per unit mass and without increasing the relative cost of an instrument.	Flagship and Probe-class X-ray missions. Explorer-class X-ray missions. Sounding rocket experiments.	**Named missions:** **Development needed for 2020 Decadal:** No **Other drivers:** Explorers, Probes, and Missions of Opportunity (MOs).

Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
Far-IR Spatio-Spectral Interferometry	Wide field-of-view spatio-spectral interferometry with cold telescopes in the Far-IR provides sensitive integral field spectroscopy with sub-arcsecond angular resolution and R ~ 3000 spectral resolving power. This technique will give the Far-IR Surveyor the measurement capabilities envisaged in the Astrophysics Roadmap. With those capabilities the community will learn how habitable conditions develop in nascent planetary systems and will overcome source confusion to measure the spectra of individual high-z galaxies, complementing JWST to understand their formation and evolution. The angular resolution achievable with a structurally connected interferometer will vastly exceed that of any practical single-aperture telescope, and the resolution, coupled with spectroscopy, is essential to mapping the distribution of water vapor and ice in protoplanetary disks. Experiments conducted with an existing laboratory testbed interferometer and parallel algorithm development are needed to advance spatio-spectral interferometry to flight-ready status for the Far-IR Surveyor. The gap can be closed in 2 to 3 years of concerted effort, and depends entirely on funding. Nearly all of the required hardware exists in an established testbed, as does the optical system model. The testbed is currently housed in a world-class facility, which offers the stability of a quiescent space environment. The graduate student and postdoc have moved on to new positions, so new qualified experimentalists will have to be hired. Current SOTA in detector technology is the only other pacing item for a far-IR interferometer, and current investments may yield detectors – TES bolometers or KIDs – that satisfy mission requirements. (The detector requirements and performance goals are relaxed relative to those for OST.) A structurally connected interferometer could enter development in the early 2020s and fly by the end of the decade. Interferometry is perceived to be complex, but the engineering challenge is greatly relaxed at long (far-IR) wavelengths. Wavefront sensing and control for JWST, a mature technology, is a harder engineering problem than far-IR spatio-spectral interferometry.	Wide field-of-view spatio-spectral interferometry has been demonstrated in the lab (GSFC) at visible wavelengths with a testbed that is functionally and operationally nearly equivalent to a space-based far-IR interferometer, and testbed experiments have been conducted with an astronomically realistic hyperspectral test scene. The most important error terms are well understood. Further, single-pixel spatio-spectral interferometry has been demonstrated in the lab (University College London) at THz frequencies, demonstrating the desired broadband far-IR wavelength response of the beam combiner. This work was the subject of two successfully-defended PhD theses, one by Dr. Roser Juanola-Parramon, and another by Dr. Alexander Iacchetta. During Dr. Juanola-Parramon's tenure as a NASA Postdoctoral Fellow, she adapted her "Far-Infrared Spectro-Spatial Space Interferometer" computational simulator to model the optical testbed.	4	4	Additional effort is required to fully characterize the hyperspectral scene projector used in the testbed, as well as minor testbed optical aberrations, and then to close the loop by demonstrating reconstruction of a hyperspectral astronomically realistic scene that matches an independent measure of the "truth" scene to high fidelity, with residual differences explained. All necessary equipment is in place to characterize the scene projector. Testbed optical aberrations will be understood with the aid of an existing, thoroughly tested computational optical system model of the testbed. Finally, experimentation with "single dish" (standard FTS) mode and simulation and experimentation with data acquired with a rotating interferometer, will close the gap and provide enabling technology for a space-based far-IR interferometer.	Interferometric baselines in the tens of meters, up to ~100 m, are required to provide the spatial resolution needed to follow up on discoveries made with the Spitzer and Herschel space telescopes, and to provide information complementary to that attainable with ALMA and JWST. The capability to definitively map the distributions of gas, dust, and ice in protoplanetary disks, to find structures (gaps or holes) indicating the presence of young planets, and to learn how the conditions for habitability arise during the planet formation process, is particularly strong motivation for the Far-IR Surveyor. Only a space-based far-IR interferometer will have these capabilities. Programmatically, as explained in the Astrophysics Roadmap, Enduring Quests, Daring Visions, the far-infrared is the best "training ground" for space-based interferometry, but eventually interferometers will be needed across the entire electromagnetic spectrum.	Wide-field spatio-spectral interferometry is the critical path technology for a Far-IR astrophysics mission consistently given high priority by the Far-IR astrophysics community since the 2000 Decadal Survey, and most recently in the NASA Astrophysics Roadmap, Enduring Quests, Daring Visions. The first interferometer will be structurally connected and might resemble the SPIRIT mission concept recommended as a Probe-class mission to the 2010 Decadal Survey (https://asd.gsfc.nasa.gov/cosmology/spirit/). Later interferometers would rely on the same technology, but could use formation flight to provide long interferometric baselines and correspondingly improved angular resolution (Harwit et al. 2006, see http://adsabs.harvard.edu/abs/2006NewAR..50..228H). The Astrophysics Roadmap explains the need for space-based interferometers across the electromagnetic spectrum, from far-infrared to X-rays. Potential applications also exist in NASA's Planetary and Earth science programs.	This technology is the pacing item for a space-based far-IR interferometer. The future envisaged in the Astrophysics Roadmap will be delayed until NASA invests to close the gap on wide-field spatio-spectral interferometry, so the urgency is great.

2019 Astrophysics Strategic Technology Gaps

Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
High-precision low-frequency radio spectrometers and interferometers	Radio spectrometers and interferometers are needed for lunar surface and orbital missions that operate below 100 MHz (>3 meters wavelength) over fractional bandwidths of 100% (e.g. 25-75 MHz) with spectral resolution of R>10^4. Relative accuracy must exceed 0.001% (1 part in 10^5) between any two channels within the band, but overall absolute accuracy is acceptable at 1%. Antennas/feeds must exhibit low reflection coefficients below -10dB across the full fractional bandwidth. Antenna/feed radiation patterns must be achromatic over the full bandwidth such that residuals to a 5th-order fit of observed Galactic sky noise are less than 0.01%. Low-power signal processing for interferometric arrays of radio systems is needed that achieves <10 pJ per CMAC. Full systems are needed that can operate through the 14-day lunar night and that meet functional requirements for robotic and/or human deployment. The technology development here is different from #16 in that the requirements are for multiple dipole antennas that must be deployed on the lunar surface and the correlation of these signals to measure the power spectrum of the first structures in the early Universe. So, #16 and #18 are sufficiently different to stand independently.	Existing flight radiometers (e.g. JUNO Microwave Radiometer, GPM Microwave Imager) have <10% fractional bandwidths and accuracy of order 1-10% across only ~10 spectral channels. Radio receivers meeting the bandwidth and resolution requirements are used on ground arrays (e.g. Tingay et al. 2013, DeBoer et al. 2017). Radio receivers meeting the accuracy requirement have been demonstrated in the laboratory and deployed for ground-based measurements (Bowman et al2018, Rogers & Bowman 2012, Monsalve 2016, 2017). Techniques such as polarimetry have been designed to improve accuracy of the separation from foregrounds (Nhan et al. 2017, 2019). Existing receivers are limited by design choices not suitable for flight, including use of mechanical radio-frequency switches. Antennas meeting the requirements have been demonstrated in simulation and validated in ground-based measurements (Mozdzen et al. 2016, 2017). Low-power cross-correlation ASICs have been designed (D'Addario & Wang 2016) and more-efficient correlator algorithms have been demonstrated on data from ground arrays (Thyagarajan et al. 2017).	4	3	1. Produce a radio receiver with bandwidth 0.5-40 MHz, 10 kHz spectral channels, and relative accuracy of 0.001% at the antenna input plane. 2. Produce an achromatic antenna with reflection coefficient less than -10dB across bandwidth and thermal stability sufficient to meet the requirement across temperature variations of 100 degrees C. 3. Produce an end-to-end low-power digital signal processing using ASICs that requires less than 10pJ per CMAC for interferometric correlation of 16 receiver systems with 100 MHz bandwidth. 4. Produce a deployable surface antenna suitable for use with robotic deployment platforms designed to assemble an array of 16 systems on the lunar far side. Produce full system design capable of operating on lunar surface through the full lunar day/night cycle (specifically addressing power and thermal constraints during lunar night).	The desired radio spectrometer performance is two orders of magnitude better than existing systems and enables missions that support NASA key science on "The History of Galaxies" and "Originals and Fate of the Universe" (Astrophysics Roadmap 2013), including the Cosmic Dawn Mapper (Astrophysics Roadmap 2013, p. 90). The desired low-power correlator reduces mass and cost of a lunar interferometer compared to baseline estimates (Lazio et al. 2011). The desired technology further enables detection of exoplanet auroral radio emission/space weather in the key band below the Earth's ionospheric cutoff (<20 MHz) from orbital or lunar surface platforms, thus enhancing future science opportunities for "Characterizing other worlds" and "Our Nearest Neighbors and the Search for Life" by improving understanding of exoplanet habitability.	Dark Ages Radio Explorer and Dark Ages Polarimeter Pathfinder (DAPPER) (Burns et al. 2017) Cosmic Dawn Mapper (Astrophysics Roadmap 2013, p. 90)	Early 2020s for a lunar orbiter demonstrator, e.g. DAPPER Burns et al. 2017; 2019) 2025 for initial lunar surface array with 128 elements, e.g. FARSIDE (ROLSS; MacDowall et al. 2011, Lazio et al. 2011; Burns et al. 2019) and coordination with Human Exploration planning

Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
Mid-IR Coronagraph Contrast	Enable the direct imaging and characterization of giant exoplanets in the mid-infrared.	The current state of the art for mid-infrared coronagraphs are the three four-quadrant phase masks of JWST-MIRI. These provide narrow-band imaging with contrasts up to 10-4 in three narrow bands from 10.65-15.5 micron with inner working angles of 0.33-0.49". The MIRI coronagraphs do not offer spectral dispersion.	3	3	Coronagraphy in the mid-IR to detect ~100-300K planets in emission and perform spectroscopy between 10-30 mm wavelength, with 2 λ/D inner working angle and of order 10^{-6} contrast. Maximum spectral dispersion should be sufficient to resolve the 15 micron CO2 band (R ~ 500).	Mid-IR coronagraphic spectroscopy would also support a variety of COR science cases, including resolved studies of solid-state features indicative of amorphous or crystalline grain mineralogy in protostellar, protoplanetary, and debris disks, as well as studies of dust and gas around evolved stars and AGN. The low mid-IR contrast ratio between hot central stars and warm surrounding dust make circumstellar dust investigations especially interesting in this wavelength range.	Origins Space Telescope, or other	Need to demonstrate credibility before the 2020 Decadal Survey, and would require TRL 6 by mission PDR anticipated in the mid-2020s.

2019 Astrophysics Strategic Technology Gaps

Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
Ultra-high-resolution focusing X-ray observatory telescope	Very high angular resolution in the X-ray band is needed to study the structure surrounding and jets emanating from SMBHs at the cores of galaxies. However, the Chandra X-ray observatory's 0.5-arcsec resolution is already near the best that can be expected from grazing-incidence reflection. Simulations suggest that above 4 keV, a transmitting diffractive-refractive pair in direct contact in which the focal length of the refractive component is minus twice that of the diffractive element can achieve milliarcsec resolution by nullifying chromatic aberration over a 15% bandwidth. However, a 1-m-diameter system would have a focal length of the order of 1000 km. Optics and detector would be aboard separate spacecraft that engage in "formation flying." Only one spacecraft can be in a true orbit; the other has to be powered by an engine to overcome the gravity gradient to maintain alignment and to reposition for target changes. The center of the detector spacecraft has to be < 10 cm from the optical axis or a designated position in a raster scan. The position of the optical axis has to be known to < 5 mm for milliarcsec resolution. Pointing direction of the optics and the distance between the two spacecraft are not critical.	This system requires new technology in two areas, X-ray optics and mission operations. Construction of the optics is not expected to be difficult; in fact, it should be much less demanding and much lower mass than a grazing-incidence optic. However, the very long focal length precludes laboratory tests of large-diameter optics. The principle but not the level of performance can be verified by testing miniature components at synchrotron radiation facilities with a very long vacuum pipe to accommodate the large distance between the optics and detector. Mission operations have to be studied analytically. No other high-energy mission or mission concept that this author knows of has had operational requirements comparable in difficulty to this, but there is no apparent reason why they cannot be satisfied.	1		The mission should be considered only after the development of a successor to Chandra (Lynx) has begun. It would begin with a study of formation flying of two spacecraft separated by 1000 km to determine the feasibility and costs of maintaining the position of the detector within 10 cm of the optical axis, or a designated point on the focal surface of a raster scan, with a positional uncertainty < 5 mm for a period of several years, during which time there will be target changes. Propulsion, most likely by ion engines, is needed for both maintaining pointing and changing targets. The quantity of propellant that can be accommodated determines the lifetime of the mission. The presence of either two optics or detector spacecraft will result in more efficient utilization of propellant. One spacecraft navigates to the next target position while the other is observing.	This X-ray telescope system offers in theory three orders-of-magnitude higher angular resolution than any current or future grazing-incidence X-ray telescope and any single-lens telescope in any wavelength band. The formation-flying capability that would be developed for this mission is applicable to an even more ambitious project, X-ray interferometry with multiple lenses. Development of formation-flying capability between two or more spacecraft should be useful in other space projects.	A very-high-angular-resolution X-ray telescope would be enabled by the development of technology for long distance formation flying between two spacecraft with 5-cm pointing accuracy of the detector with respect to the optical axis or another direction of a raster scan, and changing targets. The principal objectives are observing the structure of the environment surrounding SMBH and the small clumps of material in their jets. The same would apply to the nebula surrounding neutron stars and the jets emanating from them.	**Named missions:** **Development needed for 2020 Decadal:** No **Other drivers:** Applicability would be a decade after the next high-angular-resolution telescope, i.e. Lynx, has operated for several years, and has revealed specific targets that require higher-angular-resolution observations to probe more deeply.

Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
Very-Wide-Field Focusing instrument for Time-Domain X-Ray Astronomy	There exists considerable support in the astronomical community for a Probe-type mission dedicated to Time-Domain X-ray Astronomy. Given the large number of X-ray sources across the sky that are variable, or transient, the key instrument would be a focusing telescope with an extremely large field of view, i.e. several steradians. The type of optics with the large field of view is known as a "lobster-eye." There are two types. One is based on an array of square pores slumped onto a spherical surface. Small units have been constructed and, in fact, such an optic is scheduled to be aboard the ESA mission to Mercury. The other type of lobster-eye is a hybrid consisting of an equally spaced array of flat mirrors that lie along the radii of a cylinder. Both faces of the mirrors are coated with a heavy metal with good X-ray reflectivity. It provides position information in one dimension. A circumferential cylindrical coded mask provides positions in the other dimension. Both types require similar detector systems, which would consist of an array of CCD, CMOS or other type of pixelated detectors. While the detector chips currently exist, there has not been an array of X-ray devices that covers efficiently a very large area (up to a square meter). Compared to the 2D channel-plate optic, the hybrid has an order of magnitude more effective area and much broader bandwidth but more background. For very short-lived transients, such as gravitational waves (GWs) and short gamma-ray bursts (GRBs), where little background accumulates, the larger area and broader bandwidth is desirable.	Small prototype telescopes of both types have been constructed but are not close to the optics size required for the Transient X-ray Astrophysics Probe. Leicester University in the UK has been leading the thermally slumped channel-plate effort. So far, the angular resolution of small units has been ~5 arcmin, far short of the 20-arcsec theoretical value. Also, the coatings on the walls of the channel plate have not been optimal. Small versions of the cylindrical-geometry 1D focusing lobster-eye telescopes have been constructed at SAO and in the Czech Republic. However, the problem of a low-mass structure for the mirrors has not been addressed and no effort has been made to develop a circumferential cylindrical coded mask to go with the cylindrical 1D lobster-eye. While optical astronomers have successfully made large arrays of optical/infrared CCDs, there has not been the need so far for a comparable X-ray detector. Technologies for the channel plate version are ~TRL 4. Technologies for the hybrid exist in concept but insufficient support delays design of a prototype optic integrated with a coded mask. Optics are at ~TRL 2 and the 1D cylindrical coded mask at TRL 3 thanks to the success of Swift and XMM coded masks. The UK is supporting most channel-plate telescope development efforts. Support for the hybrid would have to be provided by NASA. The detector array for both 2D and 1D focusing systems is at TRL 3. Comparable-size arrays have been constructed for optical telescopes but with less need for continuous focal surface coverage. Kepler is an example of a large focal plane detector array in space.	Channel-plate telescope 3 – 4; cylindrical hybrid 2 – 3	4	With a 1-m focal length and 120° azimuth coverage, the lobster-eye focal plane would be a closely packed cylindrical array of pixelated X-ray detectors over a focal surface with ~1-m^2 total area. Ideally, the detector active region would occupy a very large fraction of that area, efficient to at least 10 keV, with 50-μm pixels sufficient. Telescope technical goals are several arcmin or better angular resolution and sub-arcmin position determination (by finding image centroid) with a FOV ≥ 2 ster. Sensitivity for GRB detection at least ×10 better than Swift, capable of detecting and positioning all kinds of variable (and static) sources at least ×10 better than the scanning Rossi X-ray Timing Explorer (RXTE) All-Sky Monitor and Japan's Monitor of All-sky X-ray Image (MAXI) on the International Space Station (ISS). Many sources are nearly constantly in the FOV (except during Earth occultation in Low Earth Orbit, LEO) for both types of lobster-eye telescopes. The hybrid's larger exposure time and area ensure superior sensitivity to the scanning collimated monitors, with background reduction of focusing adding another level of superiority.	Both types of lobster-eye telescopes are new types of X-ray optics that have not been in orbit. The channel-plate type will be very low mass. The FOV of both types is several ster whereas current and previous focusing telescopes, e.g. Chandra and XMM, have fields that are a fraction of a square degree. The difference in sky coverage is a factor of 10^4. Large non-focusing detectors with similar large FOVs, e.g. Swift, do not cover the same bandwidth, and have much less sensitivity and angular resolution. The lobster-eye telescopes enable an entire new class of measurements, detecting and positioning short-lived transient sources such as distant GRBs and likely transients with sub-second duration transients associated with GWs. They have much more sensitivity than the non-focusing scanning all-sky monitors for all types of temporal variations.	The very-wide-field lobster-eye X-ray telescope enables the development of the Transient Astrophysics Probe, a candidate PCOS mission that carries out studies of multiple sources varying over a large range of time scales simultaneously from the same pointing position. By detecting and positioning very distant GRBs, Cosmic Origins (COR) objectives will be fulfilled because the distant GRBs' host galaxies will be the youngest galaxies in the universe. Lobster-eye telescopes can map X-ray emission from planets and asteroids in our solar system. Depending on the viewing distance and the size of the object, X rays from a large part or the entire front-facing surface of the planet can be mapped much more quickly with the lobster-eye telescope's large FOV.	**Named missions:** **Development needed for 2020 Decadal:** No **Other drivers:** NASA is not likely to launch a Probe-type mission in less than five years. Meanwhile technology development of the optics and X-ray detector arrays can proceed via Astrophysics Research and Analysis (APRA) and SAT programs.

Gap Name	Description	Current State-of-the-Art	TRL SOTA	TRL Solution	Performance Goals and Objectives	Scientific, Engineering, and/or Programmatic Benefits	Applications and Potential Relevant Astrophysics Missions	Urgency
Wide-Bandwidth, High-Spectral-Dynamic-Range Receiving System for Low-Radio Frequency Observations on the Lunar Farside	Receiving systems consisting of an antenna and associated electronics to amplify, filter, and sample the highly redshifted neutral hydrogen signals from the Dark Ages & Cosmic Dawn, i.e., at redshifts z ≈ 10-130. The desired signals of interest have amplitudes of milli-Kelvins to potentially a few hundred milli-Kelvin (measured as brightness temperatures), relative to foreground emissions at the level of 1000 to 10,000 K, implying spectral dynamic ranges of order 1 million (60 dB). Further, signals of interest are generated over a wavelength range (bandwidth) comparable to their central wavelength (10-80 MHz).	Notional designs exist for full systems; proof-of-concept subsystems have been demonstrated in laboratory environments, and the individual components likely to be used in a full system have been demonstrated in relevant environments. A demonstration of subsystems and a full system in a relevant environment has not yet been accomplished. Temperature stabilization to 1°C measured via narrow frequency tones have demonstrated gain stability to 60 dB in the laboratory. Measurement of foreground polarization to separate the foreground from the unpolarized 21-cm signal has been demonstrated with the Cosmic Twilight Polarimeter in the field (Nhan et al. 2019).	4		The goals of a program to address this gap are two-fold: demonstrate capability to make measurements of sky-averaged highly redshifted neutral-hydrogen signals; and demonstrate capability to collect highly redshifted neutral-hydrogen signals in a manner allowing later imaging. If the first goal can be met, the technology capability required for the second goal will also be met. Specifically, measure the noise in 4 Stokes parameters to 20 mK RMS and receiver gain to 5 ppm/sec. A system capable of fulfilling these goals can be divided into three key sub-systems: I. <u>Antenna:</u> Proof-of-concept antennas able to receive signals over at least a 3:1 wavelength range have been constructed; the objective is to construct an antenna with a sufficiently stable frequency response that it changes by only a small amount over range of temperatures expected for a space-based antenna; II. <u>Analog receiver:</u> The receiver amplifies and, if needed, filters and conditions for further processing signals collected by the antenna; the receiver must allow characterization at a level sufficient to allow extraction of the cosmological hydrogen signal at a level of 1 -10 ppm of signals received by antenna; designs for such receivers have been demonstrated in the lab. the objective is to construct one in a lab environment, demonstrate its performance, and then construct one for the thermally controlled environment expected for a spacecraft; and III. <u>Digital spectrometer:</u> The spectrometer converts analog signals to digital, and forms them into spectra with sufficient spectral resolution to detect the cosmological hydrogen signal; digital spectrometers with the required performance have been developed in a lab environment; the objective is to implement a spectrometer with flight-qualified hardware in the thermally controlled environment of a spacecraft.	This technology capability would benefit studies of "Cosmic Dawn," one of the three science objectives for this decade as identified by the NWNH report. Studies of the highly redshifted neutral-hydrogen signals will probe the Epoch of Reionization (EoR) NWNH science frontier discovery area, and address the science frontier question "*What were the first objects to light up the universe and when did they do it?*" from the Origins theme. Studies of highly redshifted neutral-hydrogen signals may also be able to probe into the true Dark Ages, before any stars had formed. Such studies would complement COR objectives, and address goals of the PCOS Program.	The application is for space- and lunar-based missions designed to find highly redshifted (z≈ 10-130) signals from neutral hydrogen. Potentially relevant missions described in the Astrophysics Roadmap include a precursor lunar orbiter mission (Introduction to Chapter 6 of the Astrophysics Roadmap) ; a NASA-funded SmallSat concept study for a lunar orbiting low frequency telescope (Dark Ages Polarimeter Pathfinder, DAPPER) was recently completed. Another relevant mission is the and an eventual Cosmic Dawn Mapper also described in the Astrophysics Roadmap). A NASA-funded Probe-class design study was also recently completed for a 128 element array for a FARSIDE array.	Three years for the precursor lunar orbiter mission DAPPER.